PacMARS
Pacific Marine Arctic Regional Synthesis

Pacific Marine Arctic Regional Synthesis (PacMARS)

Final Report-Executive Summary

Citation: Grebmeier, J.M, L.W. Cooper, C.A. Ashjian, B.A. Bluhm, R.B. Campbell, K.E. Dunton, J. Moore, S. Okkonen, G. Sheffield, J. Trefry, and S.Y. Pasternak. 2015. Pacific Marine Arctic Regional Synthesis (PacMARS) Final Report, North Pacific Research Board. 259 pp. Full report available on the PacMARS website http://pacmars.cbl.umces.edu/.

EXECUTIVE SUMMARY

The Pacific Marine Arctic Regional Synthesis (PacMARS) is a research synthesis effort funded by Shell Exploration & Production Company and ConocoPhillips, and administered and managed by the North Pacific Marine Research Institute through the North Pacific Research Board in consultation with the U.S. National Science Foundation Division of Polar Programs. The goal of the **Pac**ific **M**arine **A**rctic **R**egional **S**ynthesis (**PacMARS**) effort is to facilitate new and cross-disciplinary synergies in our understanding of the marine ecosystem of the greater Bering Strait region, including the northern Bering, Chukchi and Beaufort seas. The specific objectives of the PacMARS research team and collaborators are as follows: (1) identify and synthesize existing data sets that are critical for evaluating the current state of knowledge of this marine ecosystem, including human dimensions, and (2) define the high-priority, overarching scientific themes and research needs for the next decade or more of marine ecosystem studies in the Pacific Arctic Region.

Seasonal sea ice continues to decline in the Arctic, with a record minimum observed in 2012. Offshore oil and gas exploration is anticipated in US waters and ship traffic is increasing through Bering Strait. These changes portend a different future for commercial activity, particularly if the Northern Sea Route along the north coast of Russia becomes a practical and cost-effective shipping route between Asia and Europe. The Northwest Passage through the Canadian Arctic has also become ice-free several times in recent summers, a significant change. All of the Arctic countries, including Russia, the United States, Canada, Denmark (Greenland) and Norway are exploring the limits of their arctic continental shelves to advance claims under the Law of the Sea Treaty.

Within this context of major environmental and socio-economic changes, wildlife populations and human communities are adjusting to shifts in seasonal sea ice coverage and climatic warming that has been much more obvious in the Arctic than at lower latitudes. Timing, availability, and accessibility of the subsistence harvests of marine resources by coastal residents of the Arctic are changing as stocks are altered in abundance and distribution. Productivity is also observed and forecast to change as sea ice declines and penetration of sunlight into open water increases. It is now clear that many organisms, from plankton to top predators are changing their distribution, migration and foraging patterns.

There are many important and scale-dependent reasons why the northern Bering, Chukchi and Beaufort seas – what can be termed the greater Bering Strait region - are of special concern. At the global scale (10,000 to 1,000 km) the Arctic Ocean has been transformed seasonally within the past few decades into an increasingly ice-free marine system where multi-year sea ice is now rare. The PacMARS study area is among the Earth's most prominent arenas for observing climate change and feedback regulation (e.g., impacts on ice cover/albedo and CO_2 sequestration). The through-flow of extensive freshwater runoff and nutrient-rich Pacific waters into the PacMARS study area affects circulation, stratification, productivity and ice cover in the North American basins of the Arctic Ocean and beyond. As an 'inflow shelf' communicating with the remainder of the world ocean, the northern Bering and Chukchi Sea shelves are sites of enhanced primary productivity and major biogeochemical transformations in elemental stoichiometry (e.g., N/P ratios in inorganic nutrients in response to denitrification) and carbonate saturation state (reflecting differences in carbonate buffering capacity among melting sea ice, runoff, and seawater). The entire PacMARS study area is a major migration pathway and rich habitat for globally significant populations of marine mammals and seabirds that annually migrate from as far away as the subtropical latitudes and even the South Hemisphere, respectively, to the Arctic to forage for abundant food resources. Within the Arctic, the Chukchi Sea, which together with the Bering Sea extends over the largest continental shelf in U.S. waters, has experienced the most spatially extensive loss of summer sea ice of any of the Arctic marginal seas. On a wider scale, given the scope and speed of physical changes, it is not surprising that attention is now being focused on the inevitable biogeochemical and ecological consequences for the Arctic ecosystems and human society.

At the regional scale (1,000 to 100 km) the PacMARS study area characteristically exhibits very large temporal and spatial variability, process bottlenecks and biological hotspots. As climate change progresses and ice (presumably) diminishes, "tipping-point" (i.e. threshold-based regime shifts) phenomena are likely to be observed as one set of current predictable processes (e.g., sea ice retreat, phytoplankton bloom phenology, etc.) will be replaced by a new and different set of system component processes. For example, changes in coastal polynya dynamics and extent in both the Bering and Chukchi regions will impact the modification of regional water masses, such as cold pool renewal and Pacific Winter Water formation, with attendant effects on biogeochemical processes in the near- and far-field. It is at this scale that issues involving economic exploitation/development and environmental regulation will occur, and governance and sovereignty issues arise. It is noteworthy that oil and gas exploration and potential production efforts place an urgent timescale for ecosystem understanding prior to potential disturbances.

At the local scale (<100 km) challenges arise concerning the sustainability and welfare of local communities, especially those with economic and social dependence on subsistence harvesting from the marine environment. This is the scale that community residents know best, but it is a scale that is imperfectly evaluated by scientific studies that are seeking to promote ecosystem understanding that can be generalized to the biome level. For deeper understanding at this scale, the PacMARS team recognizes the importance of two-way exchange with local residents who are predominantly Alaskan Native, both with regards to their needs and specific concerns, and also to the wealth of knowledge available from local sources at appropriate spatial scales. Productive exchange has great potential for useful advances in ethnographic and natural science research, local scale understanding of the biome, and the development of effective co-monitoring and co-management of resources.

Involvement of the arctic residents in the data-gathering process of PacMARS has had strong, two-way benefits: (1) community members become more aware of the research activities taking place in their region, (2) researchers get firsthand exposure to the questions and concerns arising from the local perspective of understanding the ecosystem and they benefit from a more holistic view of the future research needs in the region, and (3) direct involvement of arctic residents leads to potential insights from Traditional Ecological Knowledge (TEK). As part of the PacMARS effort, community contributions to the study were documented during PacMARS community meetings on St. Lawrence Island (Gambell and Savoonga), and "hub community meetings" in Barrow, Kotzebue and Nome, Alaska, with tribal council representation drawn from several surrounding smaller coastal villages.

It should be noted that the original direction of the PacMARS synthesis was to evaluate existing data on physical forcing impacts to lower trophic organisms, with the upper trophic level component undertaken simultaneously through the Synthesis of Arctic Research (SOAR) effort. Funding for SOAR from the U.S. Bureau of Ocean Energy Management (BOEM) is coordinated with the National Oceanic and Atmospheric Administration (NOAA). A major goal has been to develop manuscripts focusing on upper trophic level populations in relation to physical forcing and lower trophic level connectivity. The PacMARS project effort, by comparison included physical, chemical and biological oceanographers, with one social scientist working in coordination with our original plan for local community "hub meetings" for coastal community input. As such, the PacMARS project, in concert with products from the SOAR effort, is a first phase of a multi-dimensional, multi-agency process necessary to develop a coordinated, system level, natural and social science understanding of the changing Pacific Arctic region. We consolidated both published and unpublished data into synthesis products, including development of a composite document of available data sets and submission of summary data products to a PacMARS data archive coordinated by the Earth Observing Laboratory (EOL) at the National Center for Atmospheric Research (NCAR).

1. Report Format

The PacMARS report includes a background section for the major research topics relevant to the original objectives of the project, research themes, major findings, data gaps, and relevance of topics to local communities. We developed questions for future directions associated with the six core themes, and present a conceptual model of the Chukchi and Beaufort Sea marine system to guide future research program development. The format of the report is as followings: Chapter A provides an introduction to the PacMARS project, background on environmental and social topics, and outline of the initial research themes for the project. Chapter B summarizes the methodology used for the synthesis effort. Chapter C provides results and discussion of the PacMARS project data assimilation and findings. A notable product of the PacMARS project is Appendix G1 (the PacMARS Data Source Table), a comprehensive and annotated commentary on the perceived value of prior research in the Pacific Arctic region to our synthesis effort and the prospects for identifying insightful research questions for future consideration. Chapter D identifies the three emerging broad research themes and associated questions developed during the course of the PacMARS project. We then selected six core themes to aid in a discussion of future research program development and to identify methodological issues and approaches, data and/or knowledge gaps, and future research directions. This chapter also includes a conceptual model of the Pacific Arctic system and includes recommendations for a future research program.

In the course of the project, we identified six research foci that served as initial organizing principles for the PacMARS synthesis effort:

1. Sea Ice Cover (relationships with primary production, currents, and winds)
2. Phenology of Biological Production Cycles in Relation to Physical Environment
3. Pelagic-Benthic Coupling in Relation to Physical-Chemical Environment
4. Current State of Lower Trophic-Prey-Base and Higher Trophic Feeding Hot Spots
5. Chemical Contaminants in Water, Sediments and Biota
6. Subsistence Lifestyles in Times of Climate Change

We compiled multiple data sets and/or identified internet-based linkages to data sets while developing practical synthesis mechanisms associated with the 6 foci identified above. We utilized these data to develop programmatic themes and hypotheses for future research activities. Simultaneously, during the course of the study and meetings in local communities, the community members and representatives outlined marine issues of highest concern that focused on five major topics: (1) health, availability, and accessibility of marine mammals, fish, and seabirds, (2) fishing, hunting and food security, 3) oil extraction and mining, 4) shipping and ship traffic, and 5) sea ice, hydrography, and contaminants. We highlight the results of these community discussions in the report as well as provide a summary of the hub meetings on the PacMARS website (http://pacmars.cbl.umces.edu), also available as Appendix G8. Finally, the location of upper trophic level organisms is directly dependent on physical forcing and lower trophic level populations, thus we also identify how natural and social science can synergistically be utilized for developing coordinated research with goals of a system-level understanding of the region that serves to inform local, regional and national decision-making.

The data assembled and other synthesis products have been transferred to EOL and are publicly accessible at the PacMARS project data archive site: http://pacmars.eol.ucar.edu. The development of a data inventory, the integration of new datasets, and synthesis of this information using Geographic Information System (GIS) tools facilitated our second objective, to develop forward-looking science planning objectives and to identify science needs for a potential integrated, multi-agency research and modeling effort in the northern Bering/Chukchi/Beaufort region that could be initiated in the near future in conjunction with commitments already made by the North Pacific Research Board. This final report outlines synthesis activities undertaken by the investigators funded under this project and presents resulting products, along with a summary of future research needs.

The following meetings were held during this project (available products on the PacMARS website http://pacmars.cbl.umces.edu in parentheses):

- Sept 2012 PacMARS PI meeting, Annapolis, MD (open report)
- Dec 2012 PacMARS data meeting with PIs and collaborators, Boulder, CO (open minutes)
- Jan 2013 PacMARS/SOAR open community meeting, Anchorage, AK (open report)
- Feb-Mar 2013 PacMARS "hub" local Alaskan community meetings: Savoonga, Gambell, Barrow, Kotzebue and Nome, Alaska (open report)
- Jan 2014 PacMARS PI meeting, Anchorage, AK
- Nov 2014 PacMARS PI meeting, Center for Sustainable Forestry (Pack Forest), Eatonville, WA

In addition, there were several PacMARS PI Team conference calls, ad hoc meetings and other information exchange that served to keep status up to date and tracked milestones and the progress of synthesis activities

2. Recommended Broad-scale Research Themes and Proposed Directions for Specific System-level Studies in the Pacific Arctic

Through the course of the project we identified three broad-scale, overarching research themes and associated research topics that are pertinent to successfully launch a fully integrated ecosystem research program in the PacMARS region:

Theme 1: Impacts and connectivity of advective physical forcing and changing ice cover on ecosystem structure

Advection is a key forcing function for the Arctic marine system in general and the Pacific Arctic region in particular. Advection of water, ice and biological constituents through the Bering Strait creates the nutrient, plankton and organic carbon detrital "highway" that connects the Bering Sea to the Chukchi Sea and further to the Beaufort Sea and the Canada Basin. Inherently connected to advection, sea ice is a primary forcing factor in the PacMARS region and should be jointly considered in the context of advection. The Chukchi Sea is among the most vulnerable Arctic continental seas for ecosystem change, which has been mediated by the steep decadal decline in seasonal sea ice present in its waters; extensive proportions of shelf waters are now ice free in late summer of most years.

Theme 2: Phenology shifts as tipping points for ecosystem functionality

Phenology and extent of ice coverage are thought to regulate carbon partitioning between pelagic and benthic realms as well as impact life cycles of organisms that depend upon sea ice as habitat (e.g., walruses hauling out over the shallow continental shelf). Differences in physical and biological phenology across the Pacific Arctic region reflect system-level gradients, but spatial and temporal gaps in knowledge currently limit our understanding of ecosystem process and connectivity.

Theme 3: Dynamics within the nearshore zone

The nearshore zone (distance <20 nautical miles from coast) is the interface between human/biological communities and offshore ecosystem processes: it connects terrestrial biogeochemical systems to marine waters and oceanic carbon cycling. To improve our understanding of the Arctic estuarine system, we must enhance capacities for integrating and synthesizing spatio-temporally diverse data from observing platforms spanning the terrestrial, nearshore, and shelf domains.

The following discussion outlines the PacMARS team recommendations for future research within the six identified foci, including major findings, and knowledge/data gaps. In addition, hub meetings and interactions of PacMARS investigators with local residents over the past decades have shown that all themes considered during the PacMARS effort are in some way relevant for local residents and thus we have integrated a 'relevance to local communities' section into every theme listed below. Specific research questions that should be addressed within each theme are provided in Chapter D.

Recommended Research Direction #1: Evaluate the impacts and connectivity of a changing ice cover and physical forcing on lower trophic production and carbon cycling

Major findings: Sea ice cover has diminished dramatically over the last two decades, with later seasonal freeze up and earlier break-up, near extinction of multi-year ice in the PacMARS region, and longer ice-free periods in coastal zones. In recent years these changes in extent have been quantified regionally and on a pan-Arctic scale, from every perspective ranging from local observers to satellite sensors. Warmer summer sea surface temperatures also are observed in the northern Chukchi and fresher surface salinities in the Beaufort/Canada Basin since 2005 relative to previous years. Reduced sea ice cover also increases potential uptake of CO_2, with attendant ocean acidification and melted sea ice potentially reducing surface water alkalinity. In addition, several studies indicate that Arctic sea ice itself enhances CO_2 uptake, so a continuing reduction in sea ice by itself is likely to change the CO_2 source/sink relationship.

Knowledge/Data gaps: While PacMARS and SOAR data aggregations will enable clearer studies of ecosystem impacts of sea ice reduction on a regional scale, a comprehensive, temporally and spatially explicit carbon budget has yet to be constructed that details the sources and sinks for organic matter advected or produced locally for the Bering Strait region, Chukchi, or Beaufort seas. Uneven opportunities for data collection have made it difficult to evaluate temporal and spatial change in relation to biological production at the lower trophic levels within a systems perspective. Multiple data gaps exist, including: (1) the relationship among seasonal and interannual coverage of sea ice and primary production, (2) impacts of sea ice changes on organic carbon uptake in biota and potential sequestration to sinks, (3) impacts of sea ice cover on the balance of pelagic versus benthic carbon pathways, (4) lack of seasonal and spatial coverage for sentinel lower and upper trophic species, and (5) erosion, and wave regime studies in the nearshore coastal zone.

Relevance to Local Communities: Sea ice is of critical relevance for human communities living in the Arctic. While the typical marine science perspective places sea ice within the construct of marine systems, indigenous geographies regard icescapes as extensions of human settlement, marked by named places, travel routes, navigation markers, geophysical characteristics, and user memories. Shorefast ice provides a dynamic substrate extension to Arctic coastal communities during much of the year. Local knowledge often distinguishes many controls on animal behavior, abundance, and distribution in relation to ice conditions. Sea ice distributions are, in turn, greatly influenced by wind, with direction and intensity of wind having an impact on weather, snow, ice movement, and hunting opportunities. Among the expected changes on the part of community residents are accelerating coastal erosion and more frequent and severe storms, increased shipping traffic and planned development of petroleum resources and the potential noise and chemical disturbances associated with both. The appearance of new species with reduced sea ice cover was another concern of local observers, and is consistent with scientific observations. The importance of sea ice to coastal Arctic residents is underscored by the sustained prominence of this subject in numerous meetings, testimony, and community-based discussions. To be effective, future research programs must incorporate local community observations, participation, and purposeful outreach and education of project results.

Recommended Research Direction #2: Understand the phenology of biological production cycles in relation to the physical environment with a changing climate

Major findings: The phenology of biological production cycles is tied to the annual cycle of light in high-latitude ecosystems. This strong signal in light availability, combined with seasonal nutrient availability, typically results in a highly focused primary production peak in spring followed by a delayed peak in secondary production later in the season. Both sea ice algae and open water production exhibit a latitudinal gradient in intensity related initially to light, but controlled by a combination of light and nutrient availability. Life cycles of arctic animals are linked to the predictable timing of these peaks so that they can take full advantage of the extremely short growing season. The reproductive strategies of many zooplankton species have evolved to maximize their productivity during the growing season so that they can attain a stage of development that allows them to overwinter successfully. Many higher trophic level animals (i.e. bowhead whales and seabirds) time their migration patterns to these peaks in productivity as well, as PacMARS synthesis products have documented through aggregating multi-year efforts. The recent changes in seasonal ice coverage and the concomitant increase in light transmittance implies that production cycles may be changing with earlier open water and under-ice blooms that will lengthen the growing season and possibly increase the total productivity of the system.

Data gaps: PacMARS data aggregation efforts have visually documented the dominance of summer (and fall to some extent) measurements over the other seasons (Table D1). The largest seasonal gaps remain in winter for essentially any variable measured *in situ*. Retrospective assessments of interannual variability are limited by shifts in spatial focus of the studies over the decades. In addition, we have limited data on the cumulative effects of changing physical forcing on the timing, magnitude, and duration of biological and biogeochemical production cycles. Knowledge gaps in responses exist both in: (1) potential changes in colonization patterns and replacement of arctic endemics by subarctic populations/species, and (2) the capability of organisms to adapt and/or tolerate change. How these changes will affect the current production cycles of the arctic endemics, the potential colonization of Pacific expatriates, as well as the migration patterns and important use areas of seasonal migrants, is an open question.

Relevance to Local Communities: Community representatives during PacMARS hub meetings emphasized their *in situ* observations and concerns, specifically that changing seasonality of the marine ecosystem has the potential to displace or reduce in abundance the prey organisms of subsistence harvested upper trophic level predators (e.g., fish, seals, whales, ducks) as well as shifting the distributions of those subsistence species themselves. They expressed concerns that a shift in the timing of biological processes and the potential replacement of Arctic endemic species by subarctic populations/species affects the nutritional, cultural, and economic well-being of coastal human communities that rely on these marine resources. Changes in timing would directly affect the accessibility and availability of marine resources to communities. Additionally, a change in the body condition of marine organisms has the potential to directly affect human health as well as to exacerbate food security concerns. Range expansion by subarctic fish species may lead to the northward extension of commercial Arctic fisheries and introduce the potential for (time and space) conflicts with traditional subsistence activities, environmental disturbance (e.g. bottom trawling) and overfishing of target stocks.

Recommended Research Direction #3. Determine the role of pelagic-benthic coupling in relation to changing physical forcing and biogeochemical shifts

Major findings: On the Pacific Arctic regional scale, general spatial patterns of high and low algal and benthic biomass appear to have persisted over the past 3-4 decades, with larger variability in zooplankton densities. On the sub-regional scale, however, PacMARS and other regional synthesis efforts document region-specific variability and/or changes, or lack thereof. Pelagic algal biomass in the southern Chukchi Sea during summers after 2004 has remained consistently high in comparison with measurements from previous decades, which likely explains why key benthic depositional areas have been relatively unchanged in this region. Substantial increases in chlorophyll biomass just north of Bering Strait and along the northern shelf of the Chukchi Sea and substantial decreases in the western Chukchi/Herald Valley region during this later period (post-2004) potentially reduce carbon export to the benthos in the west, while increasing carbon export to the benthos in the northeast. In the early 2000s, pelagic-benthic coupling was very strong in the northern Chukchi Sea and western Beaufort Sea due to high primary productivity and low planktonic grazing pressure, especially during the spring ice algal/phytoplankton blooms. Our PacMARS analyses also indicate an increase in benthic biomass in the SE Chukchi Sea as a "chlorophyll and benthic biomass hotspot", implying an increased downstream deposition of more phytodetritus that is reaching somewhat further north. This is possibly the basis for the increased benthic standing stock in the NE Chukchi Sea since 2005 compared to pre-2005.

Data gaps: Improved process level understanding of the impact of changing climate forcing on the strength and direction of pelagic-benthic coupling is needed. Specifically, studies should focus on the partitioning of carbon flows between the water column and seafloor, and identify key species that will be affected by the potentially changing balance in organic carbon transfer from water column to benthos. Related to this partitioning, better understanding of mechanisms driving the development and persistence of pelagic and benthic areas of high biomass and productivity and of how those hotspots interplay with biogeochemical cycles.

Relevance to Local Communities: Carbon partitioning between the pelagic and benthic realms ultimately influences how stocks of pelagic- and benthic-feeding subsistence-harvested birds, fish and marine mammals may develop over time. The strength of pelagic-benthic coupling also determines the locations of dominant feeding sites and thereby indirectly controls access to preferred harvest species. Currently, benthic-feeding mammals (walruses and bearded seals in particular) are important subsistence food resources for coastal communities, and are dependent on concentrated and persistent benthic biomass as their food source. If walruses and bearded seals move further offshore or away from traditional feeding zones, these resources would become less available for coastal subsistence hunters. On the other hand, pelagic-dominated food webs could enhance abundance and/or availability of endemic or novel planktivorous or piscivorous predators for subsistence use. Timely knowledge of any regime shift would assist in adaptive responses.

Recommended Research Direction #4: Determine standing stocks, secondary production and food web structure of marine ecosystems in a local to regional context

Major findings: PacMARS data aggregations have documented biological patterns of composition, abundance and biomass of biological communities on a regional scale that are consistent with expected current patterns and other forcing functions. This is true for benthic fauna (>1mm), mesozooplankton, and fish. However, poor data coverage is a limitation in many nearshore areas. Synthesis results documented spatially and temporally persistent patches of high benthic biomass in contrast to large spatial and temporal variations in zooplankton standing stock. There is an overwhelming dominance of invertebrates in both diversity and standing stock over fishes. Copepod crustaceans dominate zooplankton diversity, abundance and biomass, whereas mollusks, polychaetes, crustaceans, and echinoderms dominate benthic diversity, abundance and/or biomass. Spatial distribution of marine mammals and seabirds has also improved considerably over the past decade, using visual observations and instrumental tracking methods, although understanding seasonal patterns remains a major limiting factor.

Data gaps: Gaps in biomass inventories still exist for: (1) biota missed by traditional sampling gear including krill (an important prey for bowhead whales) and deep-dwelling bivalves (an important prey for walrus), and (2) for small but likely important organisms in the food web (e.g., microzooplankton and meiobenthos). For most fauna or communities, however, data are lacking on population dynamics (i.e.

consumption, secondary production, growth and mortality). These data are required in order to model carbon flows, trophic efficiencies and understand time scales at which biomass is being produced. Such information will enable us to assess ecosystem resilience to changes or stressors. Understanding also is needed of the current role of different food source end members in Pacific Arctic food webs to evaluate the potential future roles of marine and terrestrial carbon sources under changing productivity, runoff and coastal erosion regimes. Future research planning should encourage the continuation and technological improvements to telemetry programs for marine mammals, fishes, and seabirds, as well as integration of passive acoustics more effectively into oceanographic field programs. Marine mammal vocalization data from passive acoustic arrays and animal distribution and behavioral data from satellite-linked tags help describe how, when, and why areas of preferential use are related to physical oceanographic features and phenomena. Common to this and most of the above themes is a lack of sufficient data at appropriate spatial and temporal scales to address all of the research questions identified.

Relevance to Local Communities: Biomass rich, productive and efficient food webs are intrinsic to maintaining the success of subsistence harvests. Due to the place-based nature of community harvests and limited geographic reach of traditional hunting, local-level assessments with sufficiently high resolution are as important as regional synoptic assessments. Shifting spatial distributions of subsistence species and/or changing composition of harvestable fauna will require adaptive operational strategies and have cultural implications to local communities.

Recommended Research Direction #5: Evaluate the chemical contaminant loads in sediments and biota for comparison to past studies and as a baseline for future monitoring of anthropogenic impacts of resource development

Major findings: A large data base for trace metals and polycyclic aromatic hydrocarbons (PAH) in surface sediments (with good QA/QC) shows essentially pristine sediments throughout the Chukchi and Beaufort seas. Some sediments within very small areas (<200 m around historic exploratory oil drilling sites, 6 of 35 studied to date) contain elevated concentrations of barium, chromium, copper, lead, mercury and polycyclic aromatic hydrocarbons (PAH) that can be linked to discharged drilling muds and cuttings. Sediment cores show no discernible metal or PAH contamination, even within the past 50-100 years, except for the immediate, but localized areas near past drilling sites. Time series data (1986-2006) with good QA/QC are available for metals and PAH in benthic organisms (amphipods and clams) from the coastal Beaufort Sea and show low concentrations with no significant temporal or spatial trends.

Data gaps: Little or no data for chlorinated hydrocarbons (e.g., PCBs, pesticides) exist for sediments from the Chukchi and Beaufort seas. Limited data for metals and no data for PAH or other organic contaminants are available for water samples from the PacMARS area. Very few data are available to trace biomagnification of relevant chemicals (e.g., methylmercury, chlorinated hydrocarbons) in benthic food webs and in higher trophic levels. Data and models are required to determine how chemical contaminants in sediments and seawater move through the food chain, especially to upper trophic levels, including humans. A better understanding is needed of migration routes and important feeding regions for marine mammals, fishes, and seabirds and how these regions will change with anthropogenic impacts (e.g., climate change, industrial development, increased shipping).

Relevance to Local Communities: Community hub meetings and literature review confirms local concerns about contaminant levels in marine resources. These resulting food security and public health concerns are strong and pervasive in coastal communities throughout the PacMARS study area. Even where concerns were unlikely to be linked to significant actual hazards, the paucity of available data and ineffective communication of results to coastal communities facilitates speculation at the community level. Future research programs that involve chemical contaminants should incorporate local community observations, participation, and effective/relevant outreach and education of project results. Effective/relevant outreach and education includes the need for agencies and other researchers to consider their research in the context of human health and food safety and to provide results that are understandable, relevant, and meaningful to coastal community stakeholders.

Recommended Research Direction #6: Determine the impact of changing environmental conditions and food web dynamics on subsistence lifestyles in times of climate change

Major findings: Local traditional knowledge is being increasingly appreciated in western scientific efforts and each step, even those here, provides some progress towards bridging gaps between cultures and approaches. The nearshore coastal zone is very important for the subsistence harvest of marine resources by coastal communities, and is a critical migration pathway for marine mammals and seabirds, yet it is understudied because it is inaccessible by deep-draft research vessels. Major gaps exist in the bio-geo-physical linkages in the inner coastal shelf regions of both the Chukchi and Beaufort seas, where local residents travel, hunt and fish. More studies are needed that further our understanding of the ecosystems of this riverine coastal domain and its connection to the interplay of forces from land and outer shelf regions. In addition, coastal communities engaged in traditional subsistence practices are the first to notice novel species, wildlife population status and trends, wildlife disease, first sightings of migrants, pollution events, and coastal erosion.

Data gaps: There have been impacts on food gathering practices in coastal communities throughout the study area. Practical information needed to better understand these impacts includes how local communities directly and effectively adapt to the changes in the regional ecosystem, and how changes in sea ice type, extent, and duration, as well as maritime ship noise and traffic, contaminants, and increased commercial fishing pressure will affect the distribution, migration paths and health of marine animals used for subsistence. Additionally, it is unclear how the potentially negative environmental impacts described above will affect the accessibility and availability of marine resources essential to coastal communities for human consumption. More information is required on disease vectors affecting marine resources utilized by coastal communities and related human food security and public health issues. Other concerns include the impacts of offshore resource extraction including oil drilling as well as offshore, nearshore, and onshore mining activities; impacts of warmer seawater and air temperatures on sea ice and coastal erosion, as well as the erosion/integrity of critical infrastructure (i.e. roads, buildings, ice cellars); changes in ocean current patterns and ocean fronts, and wave regimes; and the need for education and research on effective exchange and integration of knowledge and results between the research science community and local residents.

Relevance to Local Communities: Throughout the PacMARS study areas, access to key species essential for coastal subsistence harvests has become more challenging. Increased distance and related fuel costs, safety in traveling and overcoming dynamic sea ice conditions are challenges for current-day food gathering. The changing ecosystem has led to increased risks, decreased accessibility to hunted foods, and less economic stability, as well as human health, and food security concerns in communities from the northern Bering Sea to the Beaufort Sea. Additional threats include commercial ship collisions with subsistence hunters in small boats and marine mammals, pollution events, invasive species, sub-arctic species range extensions, the introduction of novel diseases, and coastal erosion that impacts accessibility and community sustainability.

3. Methodological Needs for Future Research Activities

The research gaps and recommended future directions summarized in the previous section require a wide array of approaches, methods, and tools that we do not fully catalog here, although some are mentioned in Chapter D and Table D2. Because much Arctic ecosystem research currently is conducted under the broad framework of understanding the ecosystem in the context of climate change, we stress the roles of long-term monitoring and synthetic analyses of time series data including past data collections where available. Also, we stress the need for, and usefulness of, integrating interdisciplinary results into (predictive) modeling of changing ocean conditions to evaluate responses by marine biota, human life styles and industrial activities. Finally, a robust data management strategy is needed to guide data collection, processing and archival activities for each of the research directions. The following section outlines methodological objectives, associated major advances and infrastructure, and data gaps. Specific methodological needs associated with each methodological objective to facilitate PacMARS future research activities are provided in Chapter D.

Methodological Need 1: Long-term (multi-decadal) monitoring of the environment at multiple locations in the Pacific Arctic, and

Methodological Need 2: Time series retrospective analyses and synthesis studies

Major advances/infrastructure: There are few multi-decadal time-series data sets available from Arctic regions. Physical oceanographic moorings are deployed in the northern Bering Sea, Bering Strait, NE Chukchi Sea, in Barrow Canyon, and in the western and eastern Beaufort Sea. The Distributed Biological Observatory (DBO) is a developing time-series detection array composed of latitudinal transects and moorings being occupied by an international network for physical and biological measurements, but this program provides only limited benefits for process-oriented studies in the region. There are also no consistent time-series measurements in the nearshore coastal zone, a critical region for land-marine interactions and social connectivity.

Data gaps: There are critical needs for long-term studies that can lead to interpreting year-to-year variability in the coastal system, including a more extensive network of tidal gauges for sea level determinations and infrastructure that would facilitate resolution of long-period climate signals. There are only limited biochemical sensor capabilities currently available on moorings in the Pacific Arctic region. There are no equivalents in the Pacific Arctic to the LTER (Long-term Ecological Research) sites in the Antarctic or other marine and terrestrial systems where process studies are repeated seasonally and inter-annually. A lack of spatial and temporal coverage at the systems-level means that areas of high productivity dynamics, some producing persistent hotspots of productivity on an inter-annual basis, are poorly documented, and thus the key forcing factors are not evaluated at the appropriate scales. Other data needs include comprehensive daily/annual measurements of water column light profiles, biological processes and rates, studies of wintertime distributions and physiological states of phytoplankton and zooplankton as well as the processes controlling overwintering success and survival, and controlled laboratory studies of key organisms that provide data on growth and development as a function of temperature. These data all will facilitate appropriate parameterization of models, including determination of biogeochemical transfer processes to and from the sea ice or sea surface through the water column to the seafloor.

Methodological Need 3: Modeling and future scenarios

Major advances versus data gaps: Recent physical and biochemical modeling is facilitating evaluation of current and future impacts of changing atmospheric, water mass and current flow and biochemical processes in the Pacific Arctic. However, only a few modeling efforts couple trophic level biological responses to standing stock network analyses. We conclude that there is a need for fully coupled biophysical models at process scales linking physical parameters and trophic dynamics to ecosystem-level responses.

Methodological Need 4: Development and Implementation of a Comprehensive Data Management Strategy

We also point out that for any of the recommended research to be successful, it is important to develop and implement a robust data management strategy to help guide the data collection, processing and archival activities implied in each of the research directions outlined above. Consideration of a project data policy and data management support strategy that ensures continuity and consistency in data formats, collection protocols, long-term stewardship and access to the rich data legacy coming from these research activities is essential. The PacMARS PI Team spent extensive time gathering disparate data, unifying the data formats and building synthesis datasets (Appendix G4) that were key to providing the comprehensive analysis described in the full report. A similar effort will be required in the future. The research community can make that job much easier and more efficient if attention is paid to data management best practices in advance of any major data collection effort. This includes development of a detailed and accurate metadata profile for each dataset and the provision of clear documentation that accurate data collection and processing procedures.

4. Conceptual Model and Organizing Principles for an Interdisciplinary Research Effort

We developed a conceptual model for the nearshore and offshore regions of the Chukchi and Beaufort Seas to compare and contrast similar and more distinctive processes that can be used as an ecosystem starting point for evaluation (Figure D1). Processes relating to advection of water, heat and sea ice cover and loss and biological findings organize the conceptual model, and are likely important driving forces for future studies in this region. The conceptual model represents parts of the Pacific Arctic shelves as distinct areas, where varying inflow and advective characteristics have an influence upon, and interact in, a bi-directional manner with adjoining slopes, the nearshore region, and/or lagoons.

Based on our summary of the known gaps, we propose an interdisciplinary research program that will evolve around three core topics, listed here without priority:

(1) Impacts and connectivity of advective physical forcing and changing ice cover on ecosystem structure
(2) Phenology shifts as tipping points for ecosystem functionality
(3) Dynamics within the nearshore zone

Inherent to each topic is a need for geographical and disciplinary connectivity. The two broad-scale themes: advection and phenology, could be summarized within two directions of study: (1) how advection in the Pacific Arctic is driving regional gradients between the Bering Strait, southern and northern Chukchi Sea, and Beaufort Sea, in both nearshore and shelf areas; and (2) how sea ice conditions set up the phenology of the biological system and what influences those sea ice conditions have on overall pelagic and benthic productivity.

The research directions should be addressed through retrospective, field, and modeling efforts over various time and space scales to develop a systems understanding of the potential changes in the northern Bering, Chukchi, and Beaufort seas ecosystems. Rate process studies are typically not undertaken outside of narrow seasonal opportunities, but are vital to understanding how the ecosystem functions and how it will respond to change. Seasonal coverage has been lacking in most respects for studying biological processes. Moorings and gliders provide increased observational capability for the physical and potentially, chemical measurements, but investigating biological growth rate processes, and many biological distributions, requires field observations and experiments. Understanding prey-predator relationships and trophic phasing over multiple time and space scales should be a focus of field efforts, and require temporal population studies of key trophic organisms. The potential impact of ocean acidification and contaminant burdens are of key interest to both local residents and national policy planning efforts.

Based on the PacMARS findings of temporal and spatial mismatch of legacy data, we recommend that, whenever possible, time-series studies that include a composite of moorings, gliders, satellites and field process studies be set up with consistent and standardized methodologies. In addition, building field programs in light of retrospective findings and consistent with biogeochemical model budgets will enhance development of a coherent research program and associated modeling activities. Ecosystem network analyses are recommended as tools for integrating the various disciplines and scales of data collected during the PacMARS project. For over two decades such a study has been underway at the LTER site on the west Antarctic Peninsula, and a similar, comparative, long-term, time-series program is needed for the western Arctic marine ecosystems.

Coastal communities need to be encouraged to assist in specific socio-environmental studies that address their current concerns with respect to the quality of marine subsistence foods, lifestyle, and resource allocations as commercial and industrial vessel traffic increases. Further development of community-based and researcher-community collaborative monitoring efforts are needed. Such efforts should also link communities to one another so as to allow sharing of knowledge. There is a need to integrate regional subsistence-based understanding of local food webs, including changes in predator-prey relationships experienced by local observers, to provide insight to field researchers and modelers alike.

5. Afterword and Acknowledgements

The PacMARS effort was inspired in part to document the current knowledge that is available from the wealth of prior study that has intensified over the past couple decades. It is clear that while a much more detailed ecosystem understanding of the northern Bering, Chukchi and Beaufort seas is within grasp, truly integrated knowledge of the ecosystem will require further study.

We end by first thanking the many prescient scientists who pioneered work on the Bering Strait regional ecosystem over the past half-century, which gave us a basis to initiate this synthetic review. We also thank the local residents of the region who shared their opinions and specialized, local knowledge, and the industry partners who financially supported the study. This report benefited from the constructive comments received from the PacMARS advisory committee that helped improve earlier interim versions. Finally we thank the staff of the North Pacific Research Board, particularly program manager Danielle Dickson, and participating staff of the Division of Polar Programs of the National Science Foundation for their assistance in managing our efforts.