Developing a Conceptual Model of the Arctic Marine Ecosystem

April 30 – May 2, 2013
Washington, DC

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Contents

Executive Summary

In April and May 2013, 16 ecologists, social scientists, and Arctic experts were brought together to begin development of a conceptual model of the Arctic marine ecosystem. The model is intended to provide an intellectual framework to better coordinate collaborative research in the northern Bering, Chukchi, and Beaufort seas as called for in the *Arctic Research Plan: FY2013 - 2017*. Over three days, the participants considered a strawman model of the system and discussed improvements to the model from scientific and traditional knowledge perspectives.

The participants suggested considering three main areas of focus in the region: the northern Bering and Chukchi Seas; the Beaufort Sea; and the Arctic basin. For each area, biodiversity and/or biomass was represented graphically for the benthos, mid-water column, and surface waters. A dynamic version of the graphical model was conceived in which a magnified view above each region would depict details of food webs, interaction diagrams, or important details specific to key species. Human socio-ecological system and ecosystem services would be represented in a way that allows articulation of the connections within and between them.

The participants proposed that all research questions be framed with reference to two overarching processes considered to be primary drivers of the system; 1) sea ice extent and timing and 2) advection of water northward. While those processes were believed to dominant ecosystem dynamics in the region, the participants also emphasized the significance of inputs from the broader Arctic basin and beyond.

The workshop results and input from other important synthetic efforts including the Synthesis of Arctic Research and the Pacific Marine Arctic Regional Synthesis will be collated in a conceptual model intended to serve as a roadmap for collaborative ecosystem research in the region.

Purpose and organization of the workshop

The Interagency Arctic Research Policy Committee brought 16 ecologists and Arctic experts to Washington, DC on 30 April – 2 May 2013 to begin developing a conceptual model of the Arctic marine ecosystem, as well as testable hypotheses about the future state of the ecosystem. It is anticipated that the model will be refined by the scientific community and provide a common intellectual framework for the coordination of research in the Arctic marine environment. Closely coordinated research will allow a variety of agencies and organizations to address questions specific to their individual missions while contributing to system-level understanding.

The workshop participants had expertise in inter-disciplinary ecosystem research, social science, Arctic marine ecosystems, and/or Arctic marine policy and management. Participants and their affiliations are listed in Appendix A.

In advance of the workshop, the participants reviewed a strawman conceptual model of the Arctic marine ecosystem (Appendix B) and summary papers by experts on nine topics (Appendix C). The strawman organized the ecosystem according to three distinct and interconnected regions, 1) the Bering Strait and Chukchi Sea, 2) the Beaufort Sea, and 3) the Arctic Ocean basin. It included information about the current state of knowledge with respect to physics (e.g., sea ice, advection), biology (e.g., food web structure from primary producers to top predators), and ecosystem services (e.g., subsistence harvest, resource extraction). It also addressed recent changes and paleoecology to inform hypotheses about future changes in the ecosystem. Each of the summary papers recommended additional background papers.

The workshop was moderated by staff of Office of Science and Technology Policy and the North Pacific Research Board (NPRB). The draft workshop agenda (Appendix D) was modified throughout the course of the workshop and the final agenda may be found in Appendix E. Following a brief introduction about the intended purpose of the workshop and an overview of the strawman conceptual model, participants commented on the model based on their assessment of the background reading materials. They identified any contradictions between the strawman and the subject area summaries, identified gaps in our current understanding that preclude predictions about the future (out to the year 2050), and recommended elements that would be important to include in a conceptual model. The participants identified questions that they considered the most pressing to address about Arctic marine ecosystem processes and how they might change in the future and then articulated testable hypotheses that could be used to address those questions. Finally, they suggested a framework for an Arctic conceptual model that could be used to understand the functioning and services of the ecosystem.

Framing the discussion

A stated goal of the workshop was to develop testable hypotheses about the state of the Arctic marine ecosystem from the present to 2050. The workshop participants agreed that substantial global warming is assured at least through 2050 based on the current composition of the atmosphere. Therefore, independent of any environmental practices or policies, reduction in the volume and extent of Arctic sea ice will continue and, perhaps, accelerate through mid-century at least.

The participants asserted that human impacts to the ecosystem and ecosystem services would most likely be felt on a regional or local scale. For that reason, the discussion tended to focus on processes that could be addressed on the scale of the three regions identified in the strawman conceptual model (i.e., the Bering Strait and Chukchi Sea, the Beaufort Sea, and the Arctic Basin adjacent to the Chukchi and Beaufort Seas). Nevertheless, greater understanding of regional processes could provide information that may be transferable to other areas of the Arctic.

Important elements and recommended structure of a Conceptual Model of the Arctic Marine Ecosystem

The workshop participants discussed several elements that should be included in a conceptual model of the Arctic marine ecosystem. They also discussed structuring the model to facilitate its use by a broad community representing basic and applied research, management, and policy. Recommended key elements for the model included:

INPUTS, OUTPUTS, AND FEEDBACKS

While the model will be focused on the Bering Strait, Chukchi Sea, Beaufort Sea, and adjacent Arctic Ocean basin, it should include inputs from and outputs to the global system and global-scale feedbacks.

PARSIMONY

A parsimonious approach was advocated in recognition that research initiatives cannot be comprehensive. The tradeoff between model complexity and prediction error was noted. It was recommended that the model identify important processes in broad terms and capture ideas such as rates of change and resilience. Participants suggested that research may be best focused on areas that ultimately have an effect on ecosystem services or areas in which mitigation measures may be effective.

EXPECTED CONSEQUENCES

The participants recommended that the conceptual model should articulate the expected consequences of management decisions without making value-based recommendations. Among the effects that are expected, the model should articulate which are amenable to change based on mitigation or adaptation measures.

ROLE OF HUMANS

Any conceptual model of the Arctic marine ecosystem should include consideration of humans in three ways: 1) as predators integrated within the food web, 2) as a source of perturbations to the ecosystem, and 3) as receivers of the outputs of the system in terms of ecosystem services.

PHYSICAL-BIOLOGICAL COUPLING

The tight coupling between physical forcing and trophic linkages should be described in the conceptual model, as well as any positive or negative feedbacks associated with physical drivers. For example, the role of sea ice in driving the timing and location of primary producers and the drivers (e.g., advection, current velocity) affecting their fate are important elements of the model. How these processes may change and how the effects of such change are expected to cascade through the food web are necessary considerations. The model could then inform models of alternative scenarios including not only future projected climates but also effects of natural processes and human activities.

HOTSPOTS AND HOT TIMES

Also important for consideration in the conceptual model are hotspots and their influence on the entire ecosystem. Hotspots may refer to areas characterized by high rates of biological productivity (i.e., fixation of carbon), high concentrations of biomass, high biological diversity, or areas that are of importance for the reproduction of a species. It will be important to understand what makes an area productive and mechanisms by which hotspots might change. It will also be important to call attention to retention zones and the physical drivers that create retention zones. Upper trophic level species such as seabirds and marine mammals represent natural integrators of the system and may be used as indicators of the location and timing of ephemeral hotspots. The concept of "hot times" (i.e., times that are critical to processes such as the growth of primary production or the reproduction of a species guild) was also introduced and recommended for inclusion in the conceptual model.

NON-TROPHIC INTERACTIONS

The model should consider both trophic and non-trophic interactions. For example, species may compete for resources or habitat or they may generate these for one another through mutualism. The reproductive needs of species should also be considered (e.g., ice-associated seals that rely on sea ice during breeding and nursing periods).

SEASONALITY

Seasonality of the ecosystem must be addressed by the conceptual model, and the dynamics of the ecosystem during both light and dark periods should be discussed. Light availability and the extent of seasonal sea ice are important physical drivers of the ecosystem.

VARIABILITY

Expected scales of variation in space and time of various parameters will be important in designing studies. Understanding inherent variability will be necessary to distinguish long-term trends from natural variability.

Increased variability may be an indicator of an approaching tipping point in the ecosystem that may shift it into a new state. The conceptual model should include discussion of tipping points and suggest indicators that may allow their anticipation. The model should also include discussion of particularly sensitive aspects of the ecosystem, such as places, times, and species, and how their sensitivities might compare with intrinsic variability.

ROBUSTNESS AND RESILIENCE

Robustness (i.e., resistance to change) and resilience (i.e., recovery from change) should both be addressed by the conceptual model. These can be addressed at varying scales from the robustness/resilience of an ecosystem to that of a single species.

The conceptual model should include consideration of surprises, and the model should be sufficiently plastic to allow for their inclusion. It is not clear if surprises are more likely to occur in response to human activity than to changes in the natural system. Interaction of natural processes and human interactions would seem to increase the possibility of surprises. The conceptual model should also explicitly include consideration of the underappreciated 'knowns', (i.e., the things we do know about the system). For example, traditional knowledge offers a set of observations and a way of understanding the ecosystem that is not always considered. Even within the science domain, we often fail to appreciate that other studies or other disciplines have answers that we can use. Similarly, while a complete understanding of ecosystem processes often is elusive, we may neglect the fact that we can rule out some processes. Thus, we can ignore some scenarios for processes, even if we cannot definitively identify the exact processes at work.

Processes identified as important for future study

The participants agreed that research will need to focus on physical forcing including changes in the extent and seasonality of sea ice, the strength of seasonal advection, and feedbacks associated with each. They agreed that changes in these physical drivers likely will alter the phenology and, potentially, the spatial distribution and organization of the biological system and interrupt ecosystem services.

The workshop participants recommended that studies should be structured to ensure that *a priori* hypotheses could be tested. They cautioned against testing isolated null hypotheses and drawing *a posteriori* inferences.

Each participant was asked to identify a single question about the future Arctic marine ecosystem that would be most important to address. The answers were grouped into four broad categories (sea ice, ecosystem structure and function, hotspots and productivity, and ecosystem services), and the participants were asked to develop testable hypotheses in breakout groups. The results are reported below by category. Additional questions raised by the participants, but not identified as the most pressing, appear in Appendix F.

Sea ice

Sea ice is expected to remain an important feature of the Arctic, at least over the time frame considered here. The seasonal distribution and characteristics of sea ice, however, are expected to change significantly, in particular during summer.

Questions

1. What are the mechanisms driving—and consequences of—the changing seasonality of sea ice extent and thickness?
2. Is there still a defined ice edge?
3. Is the current mix of seasonal and multiyear sea ice unstable? When the entire region's ice cover is seasonal, will that be a stable state?
4. How will the decline in summer sea ice cause a shift in the dominant species in the ecosystem?

The sea ice breakout group proposed the following testable hypotheses:

1. All local feedbacks between ice and atmosphere in summer are positive.
2. Arctic climate regulation is sourced from lower latitudes.
3. The transition from multiyear to first-year ice has caused the shifts in atmospheric circulation that support ice retreat in a positive feedback.
4. The stability of the upper water column is increasing due to changes in freshwater fluxes from ice melt, river discharge, and the Bering Sea inflow.
5. Increasing ocean stratification will result in nutrient limitations to increasing productivity over the shelf.
6. Shifts in ocean stratification will result in nutrient limitations to increasing productivity in the basin.
7. Arctic-wide sea ice cover will exhibit a stable seasonal cycle.
8. The decoupling of spring ice retreat and phenology for some key species will influence ecosystem function.
9. Loss of sea ice and snow cover modifies the atmospheric linkage between Arctic change and mid-latitude extreme weather events.
10. Ice ecosystems have lost essential functions through the loss of multiyear ice.
11. Despite increased brine rejection, the winter halocline is destabilized by turbulent mixing associated with first-year, under-ice roughness and remnant summer solar heating.
12. Changes in the ice ecosystem would alter the formation and transfer of lipids in the food web sufficiently to cause fundamental shifts in the whole Arctic ecosystem.

The group also raised the question, what do we consider ice edge processes, and how do we study them if "edge" characteristics extend into the pack ice?

Elizareta Ershova

Ecosystem structure and function

Questions

1. What are the likely impacts of changes (e.g. volume, timing) in flow of water through the Bering Strait?
2. What process are setting flow, water properties, and stratification in the system; what are their global and regional drivers and timings; and what aspects of their change have the greatest impact on the ecosystem? Can we bound future change?
3. What are the structural and process backbones that hold the ecosystem together and what are the tipping points that will lead to the breaking of the current ecosystem?
4. The paleo record provides evidence for the evolution of the Arctic system in response to punctuated episodes which uniquely control the Arctic. During resetting, especially during the early part of deglaciation, how similar are interglacial ecosystems in structure and function, and how robust are they to change?
5. How do we, in a management context, retain the resilience of the social-ecological system to unexpected changes?

The breakout group participants asked the questions, "Will flow continue as is, or will it change?" and "What is driving the flow?" and formed the following hypotheses:

1. Flow is controlled by the global hydrological cycle.
2. Flow is controlled by winds.
    a. Weaker opposing winds allow faster flow through Bering Strait into the Chukchi and Beaufort Seas.
    b. Stronger wind affects heat, nutrients, species transported into the Chukchi and Beaufort Seas.

The participants then posed the question, "What is more important, in situ Arctic secondary production or advected subarctic secondary production?" They proposed four hypotheses/questions to address this question:

1. Subarctic secondary production is more resilient to warming.
2. Predators exist that can take advantage of subarctic secondary production.
3. a. Subarctic secondary production can become resident.

   b. Subarctic secondary production can survive winter.
4. Subarctic secondary production will perturb the system in summer.

The Structure and Function group noted that 1) the Chukchi Sea ecosystem is dependent on Bering Sea spring advection, 2) the offshore food web is short, 3) the food web is lipid-rich, and 4) the length of the growing season will remain constant, therefore primary production has a maximal limit. Thus, they asked, "Does winter reset conditions in the Chukchi Sea? In the Beaufort Sea? Can we have a northern Bering Sea annex?"

Finally, they posed the question, "Can we distinguish expected interannual variability from long-term trends," and they suggested the following hypotheses:

1. Structural/functional changes will not alter the natural resilience of the ecosystem.
2. Anthropogenic forcing goes against natural change.
    a. Rates of change
    b. Kinds of change
3. Organisms with shorter life cycles adjust better than those with longer life cycles. Multicellular organisms will do better than single-celled organisms.
    a. The relative composition of short-lived and long-lived species that make up the current ecosystem will drive its resilience and robustness to change.
4. Keystone species hold the system together.
    a. Resetting the Arctic ecosystem makes it resilient.

Hotspots and productivity

Questions

1. Are hotspots mostly determined by topography and/or bathymetry and, thus, unlikely to be altered by climate changes?
2. How will physical forcing cascade through pelagic-benthic coupling?
3. What controls productivity at all levels of the ecosystem, and how are these processes affected by anthropogenic activities?
4. In the face of a highly unpredictable system, which areas are most important and biologically valuable to protect from cumulative human impacts?

The breakout group consolidated their questions as follows: What are the determinants of productivity in space and time, and what are the effects of human activity on productivity? How can human activities be managed to have a minimal impact on productivity? What are the structure and function of hotspots and does their location move?

The participants then articulated the following hypotheses/ points for consideration for future study:

The following set of hypotheses are not mutually-exclusive and could be tested in succession:

H1: Spatial patterns of productivity are controlled by physiographic and oceanographic features (e.g., tidal mixing fronts) that are persistent.

H2: Spatial patterns of productivity are controlled by oceanographic features (e.g., stratification) that are affected by climate change.

H3: Benthic-pelagic coupling controls the location of hotpots for benthic-feeding species (e.g., walrus) that are affected by climate change.

H4: Overall patterns of productivity are controlled by bottom-up mechanisms involving nutrient inputs.

H5: Overall patterns of productivity are controlled by top-down forcing and impacts on top predators result in trophic cascades.

H6: Increased volume transport through Bering Strait and earlier arrival of zooplankton advected into the Chukchi Sea will increase the breeding range of small auklets northward.

H7: In the spring, bowhead whales will regularly forage at hotspot east of Point Barrow created by topographically-steered currents and dependent on wind direction.

H8: Bowhead whales will follow the ice-edge bloom out over the ocean basin whereas beluga whales will continue to forage along the shelf break.

H9: Bowhead whales will continue to return along Beaufort Sea coast in fall and whale hunts will continue to be conducted from communities located there.

Additional considerations for future study also were identified:

1. Quality and quantity of productivity is controlled by the timing and extent of sea ice.
2. The confluence of water that is high in nutrients and topographic features may result in persistent hotspots.
3. Most hotspot locations are determined by topography and/or bathymetry and thus will not be affected by climate-ocean changes. Thus, climate-ocean changes will not displace predictably located, abundant prey (i.e., hotspots) necessary for successful foraging by central place (e.g., seabirds while nurturing young) and hotspot (e.g., baleen whales) foragers.
4. Certain species, like walrus, forage on limited food types and these food types are place-specific and for those species hotspots are essential.
5. Some hotspots are persistent and are proximate to human communities where subsistence is an important part of culture.
6. Humans cannot control productivity of hotspots or create hotspots, but they can protect hotspots that exist.
7. Hotspots might be the last food refugia in an acidifying ocean, and the survival of species may depend on them.
8. Oil and gas leases should avoid persistent hotspots. Walrus are likely to increase their local impacts as they shift from dispersed foraging from ice platforms to central place foraging from terrestrial haulouts.

Ecosystem Services

Questions

1. In what ways, at what scales, and where, do human activities in the Arctic marine region affect the structure or functioning of the ecosystem, services provided by that ecosystem to humans, or access by humans to those ecosystem services?
2. Defining "risk" as the product of likelihood and impact, what are the biggest risks to the ecosystem and the services it provides and how do we reduce those risks?
3. What surprises might be anticipated that would be the most challenging to deal with, and what can we do to anticipate those or create a buffer to mitigate their effects?
4. How will choices that we make with regard to resource extraction in the Arctic affect the ecosystem's capacity to support a subsistence livelihood for Arctic people?

The participants discussed the fact that the system is destined to change profoundly and asked what would be necessary to preserve ecosystem services. They discussed the following:

1. Existing observational data are insufficient to promote the development of robust hypotheses. An approach based on monitoring and parameterized computer modeling was recommended.
2. Arctic cod populations are at risk under a changing climate, and genomic data are needed to better understand population structure and the capacity to adjust to those changes.
3. As more southerly species extend their ranges northward, biodiversity (and possibly competition) may increase.
4. Invasive species will alter the food web and trigger trophic cascades (e.g., orca predation on other Arctic marine mammals or Arctic cod).
5. Bivalves are especially susceptible to changes in ocean chemistry that will have negative implications for marine mammal foraging.
6. Harmful algal blooms will add toxins to the food web with negative implications for human consumption. Attention must be paid to stream runoff and ballast water discharge resulting from increases in vessel traffic.
7. Subsistence hunters will have increased access to marine mammals in open water but decreased access to the lead system, and the consequences of these changes are unknown.

Melany Zimmerman

Development of figures to illustrate the conceptual model framework

The working group participants suggested several distinct and complementary methods of illustrating their recommendations for a framework for an Arctic marine ecosystem conceptual model.

Figure 1 illustrates a framework for process studies and linkages within the Arctic marine ecosystem during seasons with enough light to support the growth of primary production (i.e., spring, summer, and fall).

The three main areas of focus (the northern Bering and Chukchi Seas, the Beaufort Sea, and the Arctic basin) as well as the upstream southern Bering Sea, are illustrated in three vertical planes representing the benthos, mid-water column, and surface waters. Biodiversity and/or biomass could be represented graphically in each stratum.

Expanded above each region is a magnified view that could be used to depict details of food webs, interaction diagrams, or important details specific to key species. The area explicitly overlaps bubbles representing the human socio-ecological system and ecosystem services, conveying that research questions should articulate connections within and between these.

Two overarching processes considered to be primary drivers of the system are 1) sea ice extent and timing (illustrated by the shading of each regional bubble that increases in proportion of area covered from south to north) and 2) advection of water northward (illustrated

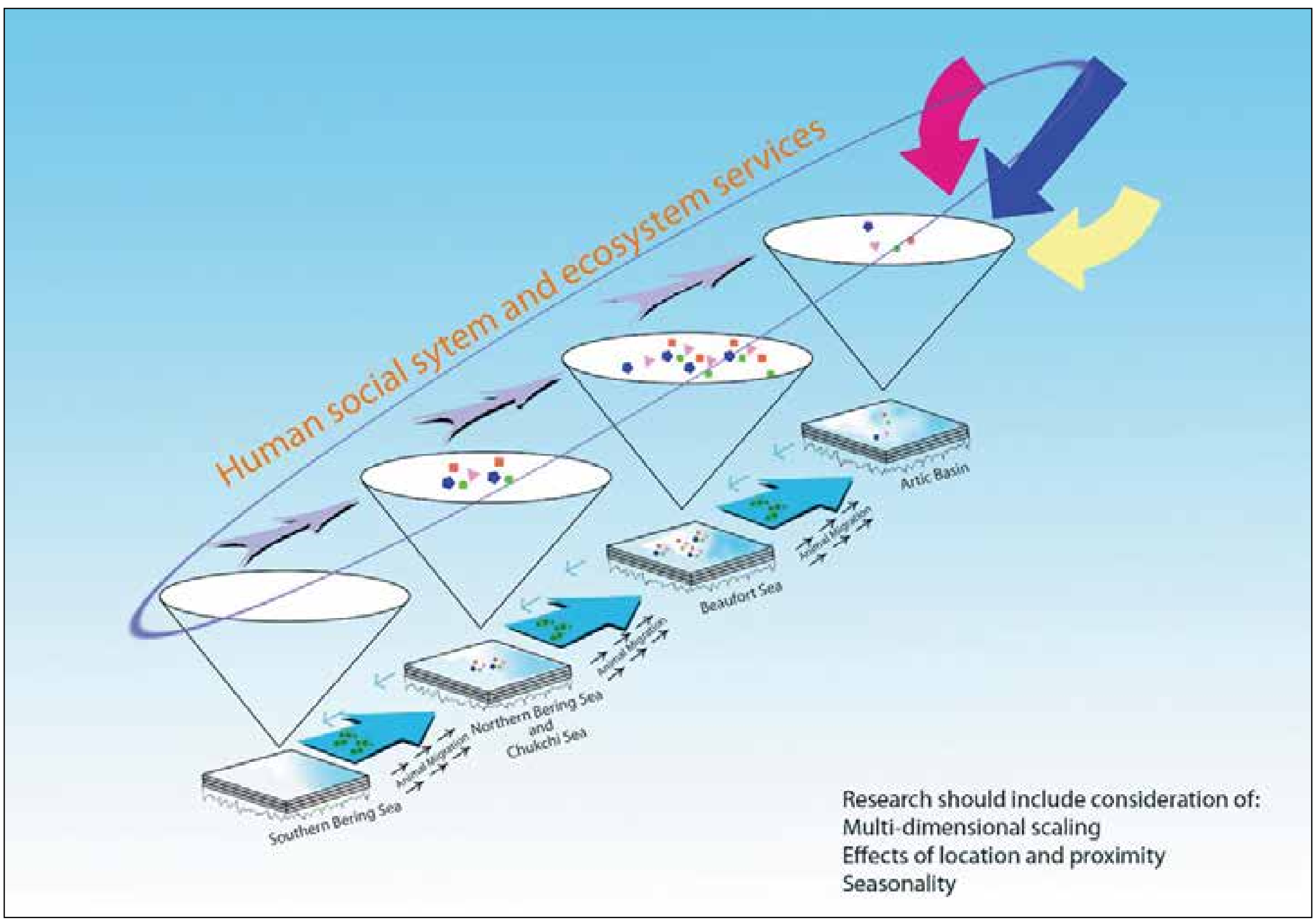


FIG. 1. SYSTEM FRAMEWORK FOR THE ARCTIC MARINE ECOSYSTEM DURING SEASONS WITH ENOUGH LIGHT TO SUPPORT THE GROWTH OF PRIMARY PRODUCTION (I.E., SPRING, SUMMER, AND FALL).

by the arrows that indicate flow from south to north). In this approach, these two elements should frame any research question posed. Additional arrows in the upper-right corner of the diagram represent inputs from the broader Arctic basin, global inputs, sea ice drivers, etc. Arrows that flow north to south between the regions represent opportunities for reversals of water flow or feedbacks that might propagate from north to south.

Figure 2 illustrates a framework for the Arctic marine ecosystem during seasons without enough light to support the growth of primary production (i.e., winter).

The structure is the same as Figure 1, with a few important differences. The thickness and extent of the sea ice is increased in all three regions. The strength of the northward flow of water decreases with increasing latitude and advection is limited to only nutrients as opposed to also including primary or secondary production. Light levels decrease to the point of complete darkness at higher latitudes. The biological system is less complex and fewer species are represented in the food web. Species migrate southward instead of northward, in contrast to Figure 1. Less overlap exists between humans and the living components of the marine environment in winter as less species are extracted from the system during those months. The connectivity between human communities in the different regions changes during winter because humans rely on sea ice for transport. Some of the anthropogenic effects, such as shipping, disappear in winter, but others, such as the global economy, remain.

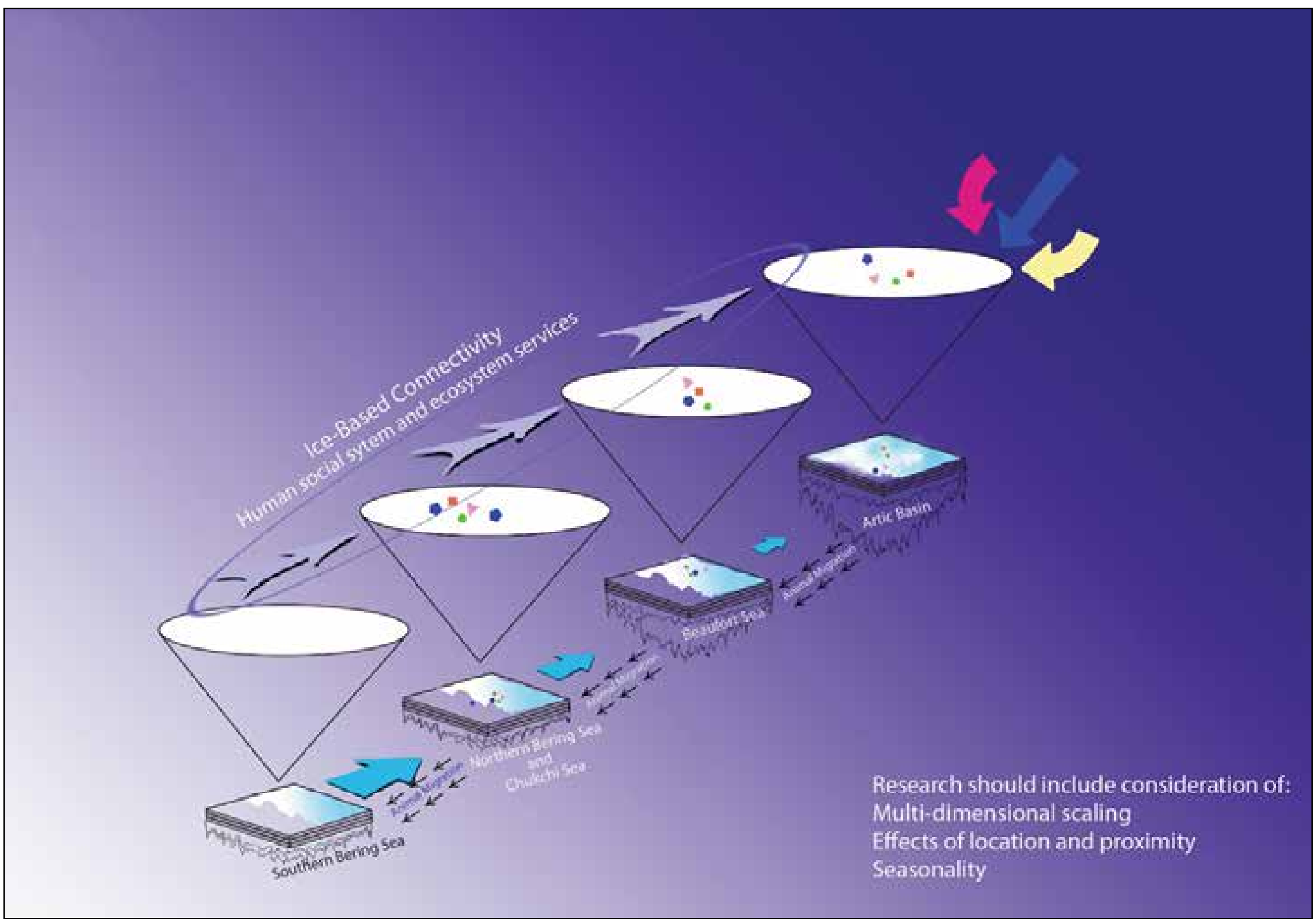


FIG. 2. SYSTEM FRAMEWORK FOR THE ARCTIC MARINE ECOSYSTEM DURING SEASONS WITHOUT ENOUGH LIGHT TO SUPPORT THE GROWTH OF PRIMARY PRODUCTION (I.E., WINTER).

Figure 3 illustrates an approach to framing a set of research questions by which one first considers perturbations to the ecosystem, followed by consideration of any feedbacks associated with those perturbations, the effects that may lead to decoupling of the system (between components and/or in space and time), the robustness and resilience of the ecosystem to such decoupling, and finally the expected effects on ecosystem services.

Two approaches to using this diagram were articulated: 1)to address perturbations over which we have no immediate or regional control (e.g., climate change) and 2) to address local human impacts that are tractable and manageable (e.g., shipping). Below are examples of these approaches.

NESTED APPROACH

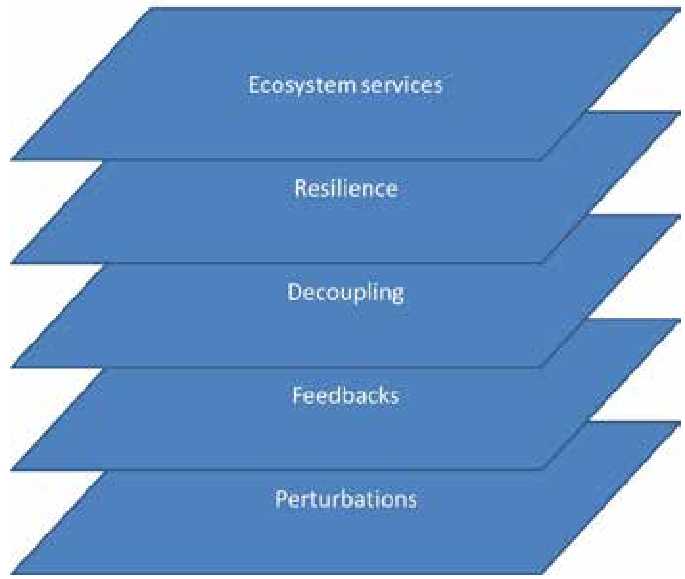


FIG. 3. A LAYERED APPROACH TO FRAMING A SET OF RESEARCH QUESTIONS THAT BEGINS WITH IDENTIFYING PERTURBATIONS TO THE ECOSYSTEM AND ULTIMATELY IDENTIFIES THE EFFECTS OF THOSE PERTURBATIONS ON ECOSYSTEM SERVICES.

[1]
BEYOND IMMEDIATE OR REGIONAL CONTROL

Perturbation: greenhouse gases are released, leading to warming, and there is an atmospheric circulation response.

Feedback: ice albedo, ice storms, climate storms

Decoupling/Recoupling: jet stream-storm decoupling, ice/ocean-storm decoupling

Resilience/Adaptation opportunities: archaeological investigations, emergency management, zoning of infrastructure, better forecasts

Impacts to ecosystem services: decreased safety, coastal erosion, loss of artifacts, threat to life and limb

Testable hypotheses: Storms follow the ice edge; Access to the ocean for subsistence activities can be accomplished by another means; jet stream decoupling will be a persistent feature of storms; Material is available for structures.

Information needs: cost and feasibility of building structures; detailed analysis of storm dynamics; knowledge about deep-water harbors.

[2]
TRACTABLE AND MANAGEABLE

Perturbation: shipping

Feedback: displacement of animals, disruption of hunting

Decoupling/Recoupling: village location suboptimal for hunting

Resilience/Adaptation opportunities: vessel management

Impacts to ecosystem services: decreased safety, decreased hunting efficiency

Testable hypotheses: marine mammal distribution will shift due to vessel traffic; locations for hunting whales will shift and be more diffuse.

Information needs: hunting locations, vessel path information

Figure 4 illustrates a matrix approach to articulating the time and spatial scales of perturbations and their effects at varying levels of the ecosystem, from physical drivers to ecosystem structure and function, to ecosystem services. This approach provides context for the effects of perturbations and informs the practical application of mitigation measures.

Figure 5 illustrates opportunities for choices in terms of management and mitigation of changes to the ecosystem and the tradeoffs associated with policy decisions.

The train carries elements such as human population, consumption rates, and resource demand through the system at a speed that is variable on tracks that lead to different states of the Arctic marine ecosystem. Our train is already on a track that is the legacy of the greenhouse effect of the 1960's and we are approaching a "global and Arctic policy" switch that can decide on which track this train will continue. The figures with control of the switch represent the combination of people at different scales, the Indigenous People of the Arctic, the United States of America, and the global community. Our potential tracks will lead us to different scenarios representing the state of the Arctic marine ecosystem. We have already missed the opportunity to return to the state that the Arctic would have looked like in the 1970's in the absence of greenhouse gas emissions. From left to right, one track leads to a heavily impacted ecosystem where sea ice is absent in the summer and storms and coastal erosion are common. Marine mammals from lower latitudes will be seasonally present. Another track leads to a system that is highly variable, with impacted areas but also some stable hotspots that remain. One track represents the effects of unknown perturbations on the ecosystem that have not been anticipated (black swans theory) that could drive the system into states yet unknown. Finally, some actions may lead to a healthy ecosystem with seasonal sea ice and with benthic-pelagic coupling maintained.

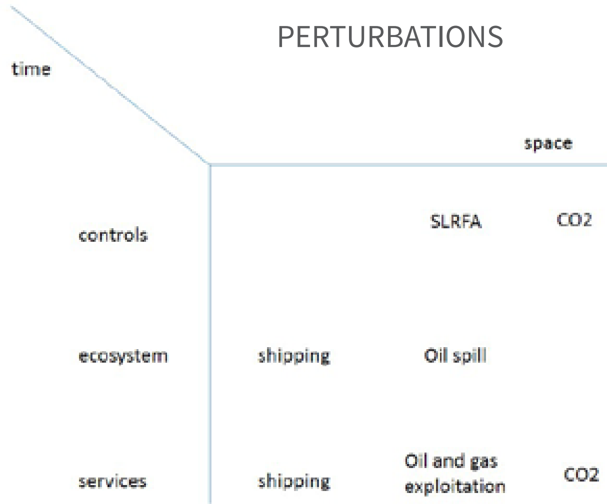
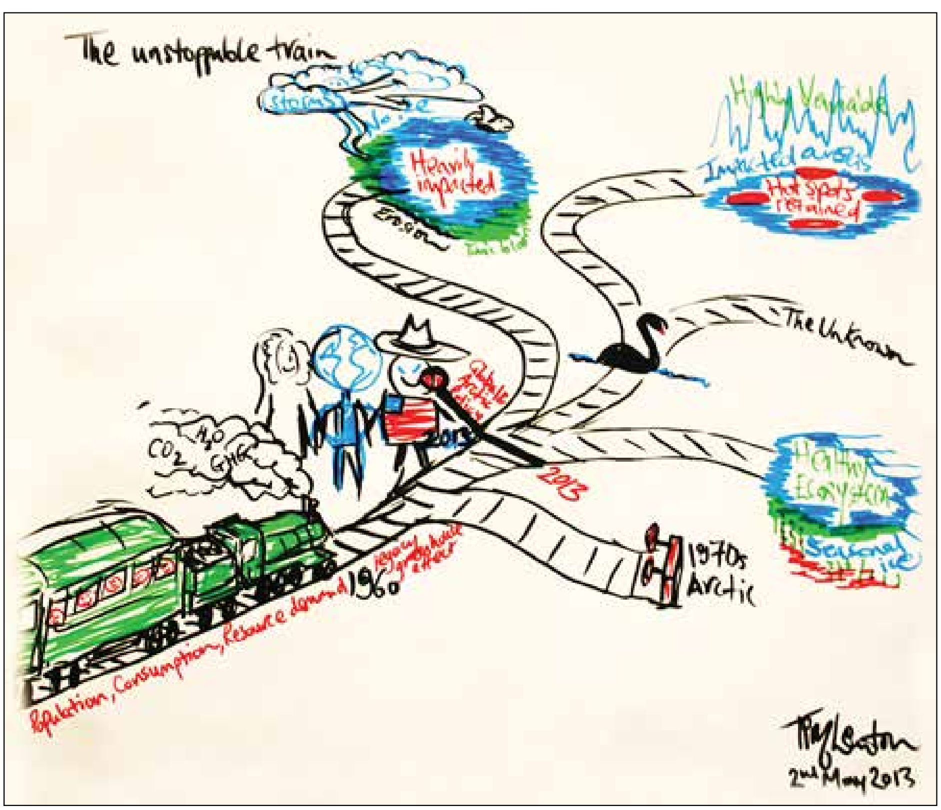


FIG. 4. MATRIX FOR IDENTIFYING THE TIME AND SPATIAL SCALES OF PERTURBATIONS AT VARYING LEVELS FROM PHYSICAL DRIVERS TO ECOSYSTEM STRUCTURE AND FUNCTION TO ECOSYSTEM SERVICES.



Tim Lenton

FIG. 5. ILLUSTRATION OF THE EFFECTS OF VARIOUS POLICY DECISIONS ON THE INTEGRITY OF THE ARCTIC MARINE ECOSYSTEM.

Marcus Janout

Concluding remarks

Understanding and depicting the functioning of whole ecosystems is notoriously challenging (Peters et al. 2008) and all the more so in the face of rapidly changing forcing mechanisms (Marshall et al. 2008). The Arctic has experienced especially rapid and dramatic changes in physical forcing. In the past few decades, warming ocean and atmospheric temperatures have contributed to a 50% reduction in summer sea ice extents and an 80% reduction in sea ice thickness. Models consistently forecast continued diminishing Arctic sea ice for at least a century. Forecasting ecosystem responses will require considerably greater understanding of the system and likely perturbations.

Federal and state governments, industry, and conservation organizations are conducting and/or planning considerable research in the northern Bering, Chukchi, and Beaufort seas. While each of those efforts has a specific focus, in combination they can increase our whole-system understanding if appropriately coordinated. The Interagency Arctic Research Policy Committee outlined the need for such coordination in its Arctic Research Plan: FY2013-2017 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/2013_arctic_research_plan.pdf). This workshop was a necessary but insufficient step toward coordinating federal and non-federal research in the region so that a more complete understanding might emerge.

The workshop results and input from other important synthetic efforts including the Synthesis of Arctic Research and the Pacific Marine Arctic Regional Synthesis will be collated in a conceptual model intended to serve as a roadmap for collaborative ecosystem research in the region. The expectation is not that we can accurately model the system and its responses with present knowledge but, rather, to provide an intellectual framework around which coordinated studies can be conducted.

Marshall JD, Blair JM, Peters DPC, Okin G, Rango A, and Williams M. 2008. Predicting and understanding ecosystem responses to climate change at continental scales. Front Ecol Environ 2008; 6(5): 273–280, doi:10.1890/070165.

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APPENDIX A
Participant List

Participants

JoLynn Carroll – University Tromsø, Norway
Carlos Duarte – University of Western Australia and Spanish National Research Council
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Sara Bowden – Executive Secretary, Interagency Arctic Research Policy Committee
Danielle Dickson – Program Manager, North Pacific Research Board
Martin Jeffries – Program Officer and Science Advisor, Office of Naval Research
Brendan Kelly (Moderator) – Assistant Director, Polar Sciences, Office of Science and Technology Policy
Richard Merrick – Director, Scientific Programs and Chief Science Advisor, NOAA Fisheries, National Oceanic and Atmospheric Administration, Department of Commerce
Melanie Russ – Project Coordinator, University Corporation for Atmospheric Research
Simon Stephenson – Section Head, Arctic Division, National Science Foundation
Neil Swanberg – Director, Arctic System Science Program, National Science Foundation
Alan Thornhill – Director of Science Quality and Integrity, United States Geological Survey
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APPENDIX B

Strawman Conceptual Ecosystem Model for the Chukchi and Beaufort Seas

Discussion Whitepaper

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April 12, 2013

Outline

I. Background

II. Conceptual Model Approach and Overview

III. The Present
- A. Key Elements and Controlling Processes
  1. Northern Bering and Chukchi Seas
  2. Beaufort Sea Shelf
  3. Pacific Arctic Basin
- B. Biological Hotspots
- C. Key physical, biological, and human thematic drivers, linkages, and feedbacks
- D. Stressors and their ecological implications

IV. The Recent Past
- A. Physical
- B. Biological
- C. Socio-cultural
- D. Traditional knowledge

V. The Future
- A. Lessons learned from the Paleo-Past
- B. Future Issues to consider
  1. Potential drivers and stressors
  2. Potential ecological effects
  3. Potential socio-cultural-economic effects

References

I. Background

The Arctic has become a region of considerable interest to the U.S. government. It is the only region called out as a priority objective in the National Ocean Policy. In the last few years, interest has increased in oil and gas development in the Chukchi and Beaufort as well as in the role this region plays in global climate change, Homeland Security, and shipping. This level of attention will persist for the foreseeable future, and has significantly inspired the Interagency Arctic Research Policy Committee (IARPC) to develop a 5-year research plan for 2013-2017 (referred to as IARPC's 5-year Arctic Research Plan http://www.whitehouse.gov/sites/default/files/microsites/ostp/2013_arctic_research_plan.pdf).

The National Ocean Council and the Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska have proposed a comprehensive, multi-agency science-based approach when addressing energy and other development issues in the Arctic. The Administration also is preparing—for the first time—a National Strategy for the Arctic region.

An important step in the design of a newly coordinated research program in the Arctic marine ecosystem is the development of a conceptual model of what the Arctic may look like in the future, and what the main information needs will be. This will help to:

- Anticipate how contemporary Arctic ecosystems—including their physical, biological, and human components—may change over the next few decades;
- Provide guidance on how anthropogenic activities can be directed to mitigate human and natural impacts on the ecosystem and facilitate human adaptations.

The IARPC Beaufort-Chukchi Ecosystems Implementation Team has agreed that a common conceptual model of a future Arctic marine ecosystem is a fundamental milepost in developing a coordinated program to understand and monitor the Arctic ecosystem. Such a program should be designed to better understand how contemporary Arctic marine ecosystems may change as a result of environmental fluctuations.

Developing such a conceptual model will build off what is already known about the U.S. Arctic and will be combined with outcomes from several ongoing Arctic marine synthesis efforts, e.g. the Pacific Marine Arctic Regional Synthesis (PacMARS http://pacmars.cbl.umces.edu/) and the Synthesis Of Arctic Research (SOAR http://www.arctic.noaa.gov/soar/) and ultimately made available to the community for research and educational purposes.

II. Conceptual Model Approach and Overview

This conceptual model focuses on the area of the Arctic within the United States EEZ but recognizes the need to understand the broader dynamics within the Arctic Ocean (AO). We thus consider the region of interest to start north of St. Lawrence Island and include the Chukchi and Beaufort Seas and the Arctic Basin adjacent to them (Figure 1).

Ecosystem dynamics are a function of a) Place-based physical drivers: currents (advection), atmosphere (radiation, atmospheric pressure, winds), stratification, and freshwater fluxes; b) condition-based interaction between sea-ice (seasonal vs. continuous) and shelf (on, edge, off); and c) trophic-based interaction among the different ecosystem components, including human interactions and drivers; with interactions between all three functions.

We classify three placed-based geographic regions within our area of interest based on bathymetry, currents, and distinct ecological differences:

1. Inflow northern Bering Sea/Chukchi shelf dominated by advection and topographically-steered flows,
2. Interior Beaufort shelf mainly controlled by wind forcing and river runoff, and
3. Arctic Basin, characterized by the Beaufort Gyre and the influence of Deep Atlantic Water.

We provide a region-independent condition-based approach (based primarily on Carmack and Wassman 2006, Carmack and McLaughlin 2011, Wassman 2011) that can be tied to locations and is useful to understand future changes in physics and biology and for spatio-temporal comparisons in our area of interest (Figures 2 and 3). They conceptually divide the entire AO into three subtypes based on its response to external drivers:

a) α-oceans, characterized by a temperature-dominated stratification and being ice free year round,
b) β-oceans, characterized by a salinity-dominated stratification and seasonal sea ice coverage,
c) Multiyear ice oceans (MYI) which occupy the northernmost latitudes of the AO.

We also provide a trophic-based framework based on current conditions with placeholders that will allow for the incorporation of future changes (Figures 4-6). In that context, future conditions can also be informed by 'paleo-scenarios' which provide us with a range of possible futures within which to consider impacts on northern food webs.

We further expand the framework by including human interactions, drivers, and well-being (e.g. Francis et al. 2009). These can be linked to current and future states and the three-way interactions mentioned above. Finally we will insert spatial connectivity between place-based states so as to consider tele-connections and barriers that may change or remain in the future.

III. The Present

A. Key Elements, Controlling Processes, and Linkages in Arctic marine ecosystems

The Arctic Ocean (AO) occupies a roughly circular basin and covers an area of about 14,056,000 km^2 (5,427,000 mi^2), almost the size of Russia. The coastline is 45,390 km (28,200 mi) long. It is surrounded by the land masses of Eurasia, North America, Greenland, and by several islands. Its maximum depth is 5,502 m with the deepest areas forming a bowl-like basin surrounded by shallow shelves on which numerous rivers and streams discharge their waters, nutrients, and sediments (Figure 7). The AO connects the Pacific Ocean through the shallow Bering Strait (shallow) with the Atlantic Ocean through the (deep) Fram and (shallow) Davis Straits.

1. Northern Bering and Chukchi Seas

The Chukchi Sea is a shallow (average depth of 80m) inflow shelf β-ocean that remains ice-covered throughout the winter, well mixed from fall through spring, and is stratified in summer due to the input of relatively warm Alaska Coastal Water (Woodgate et al., 2005b, Woodgate et al., 2010). Ice retreat in the Chukchi Sea begins in May or early June with melting driven by solar radiation and advection of relatively warm waters from the Bering Sea. The system is fed by currents that enter through the narrow (< 90 km), shallow (<55 m) Bering Strait, driven by a sea level difference between the Atlantic and Pacific oceans (Figure. 1). The Alaska Coastal Current, influenced by the discharge from the Yukon River, brings warm, low-salinity water into the area and carries few nutrients after the spring bloom. Bering Sea Water, which is a mixture of nutrient-rich Anadyr Water from the west and Bering Shelf Water from the south, accounts for more than 80% of the input (Coachman et al., 1975). In the extreme western Chukchi Sea, the seasonal Siberian Coastal Current flows southward along the coast in some years, carrying cold, fresh water (Weingartner et al., 1999).

As the currents flow northward through the Chukchi driven by topography, they respond strongly to winds, especially on the eastern side (Woodgate et al., 2005b), and along the three main canyons, where upwelling occurs in response to wind (e.g., Bourke and Paquette, 1976; Aagaard and Roach, 1990; Woodgate et al., 2005a). The continuous influx of nutrients maintains high levels of primary production seasonally, especially in the Bering Strait and in canyons in the northern Chukchi Sea (Sambrotto et al. 1984; Springer et al. 1996; Macdonald et al. 2004; Morse 2007). The nutrient system may be reset each winter on the Bering and Chukchi shelves, but that dynamic is poorly understood and may contribute to the considerable inter-annual variability in primary production. Primary production is further dependent on the timing of ice-melt, which affects the length of the growing season, the strength of wind mixing, and availability of nutrients in the upper mixed layer of stratified waters. So, whereas the currents create a supply of nutrients for production, the topography and the winds enhance it and create retention mechanisms that result in biological hotspots (see below).

Zooplankton are advected seasonally from the Bering Sea, and abundance and species composition depend on the origin of the water mass and time of year (Hopcroft et al. 2010). Biomass peaks on the northern Bering Sea shelf in early July, with likely maximum numbers in the Chukchi Sea in late July or early August (Springer et al. 1989). Zooplankton biomass is higher in years preceded by cold Bering Sea winters and is a driving factor in the seasonal abundance of planktivorous seabirds in the Chukchi (A. Gall per. comm.).

Light-limitation, low temperatures, timing of ice-melt, and the nature of zooplankton advection result in the export of the majority of the primary and secondary production to the benthos. Although export rates vary greatly by location (topography), resulting in regional benthic hotspots, the biomass of the benthos in the Chukchi Sea far exceeds that of the pelagic system (Dunton et al., 2005, Moran et al. 2005, Grebmeier et al., 2006a Lepore et al. 2007, Campbell et al., 2009). Benthic communities under the cold, highly productive Bering Shelf-Anadyr Water are moderately homogenous and dominated by a high biomass of amphipods and bivalves (Grebmeier and McRoy 1989). A more diverse, but lower biomass fauna exists in benthic communities under warmer, less productive Alaska Coastal Water, which includes amphipods and bivalves, as well as crustaceans, polychaetes and sand dollars. Faunal benthic diversity generally increases to the north in the Chukchi Sea, where food availability in bottom water and surface sediments is greater and more heterogeneous, and where finer-grain sediments occur (Grebmeier and McRoy 1989, Feder et al. 1994).

Due to this high benthic production, fish biomass is dominated by benthic species, such as sculpins. Pelagic fish assemblages are dominated by Arctic cod (*Boreogadus saida*), with older Arctic cod also observed on the benthos. Arctic cod is a pivotal species in Arctic marine systems and forages primarily on crustaceans and algae in the sea ice during its pelagic phase. It is the single most important forage fish in the region, providing the bulk of the diets of ringed seals, beluga whales and piscivorous seabirds (Morse 2007). Other common species include saffron cod (*Eleginus gracilis*), Bering flounder (*Hippoglossoides robustus*), and Pacific herring (*Clupea pallasii).*

Arctic coastal lagoon systems, such as the barrier islands in the Chukchi Sea, are an important breeding habitat for waterfowl, gulls, and some seabirds (Morse 2007). Due to the low pelagic fish biomass, planktivorous seabirds (small auklets, *Aethia* spp. and murres *Uria* spp.) are the most abundant breeding seabirds in the region (USFWS, 2003), even though their numbers are probably restricted by the number of suitable nesting sites for cliff-nesting species. The region also supports numerous migrants, including red phalaropes (*Phalaropus fulicarius*) and short-tailed shearwaters (*Puffinus tenuirostris)* (Piatt and Springer, 2003), both of which are planktivores. Nesting and migrant species take advantage of the large, lipid-rich copepods and euphausiids advected northward in Bering Sea Water. In addition, the area around St Lawrence Island supports the world population of the benthic feeding spectacled eider *(Somateria fischeri*) in the spring, whose prey base has changed and is heavily influenced by patterns in sea ice and export to the benthos (Lovvorn et al. 2009, Larned et al. 2012).

The marine mammal fauna of the Chukchi Sea include a large complement of benthic-foraging species, in particular walruses (*Odobenus rosmarus*), bearded seals (*Erignathus barbatus*), and gray whales (*Eschrichtius robustus*; Highsmith et al., 2006, Dehn et al., 2007). Bowhead whales (*Balaena mysticetus*) are abundant in the area, and although they seem to be mainly planktivores, they have been seen feeding on epibenthic prey, in very shallow water (<20 m) (Moore et al., 2010). Other pelagic foragers include spotted (*Phoca largha*), ringed (*Phoca hispida*), and ribbon seals (*Histriophoca fasciata*) that feed mostly on fish and large zooplankton (Dehn et al., 2007). Ringed seals feeding on epibenthic prey have also been documented.

Walruses and ice-associated seals gain refuge (albeit not complete) from predation by resting, molting, and rearing young on sea ice (Fay 1974; Kelly 2001). In April and May, ribbon, spotted, and some bearded seals, give birth and nurse their young on the ice edge of the Bering Sea. Most bearded seals and walruses rear their young further into the pack ice; the former in April and May, the latter starting in February. Ringed seals are widely distributed in shore-fast and pack ice of the entire region and give birth in snow dens excavated above breathing holes in the ice (Burns 1970; Kelly et al. 2010). Remnants of melting ice in the northern Bering and Chukchi seas are important as resting sites for molting seals and walruses. Polar bears (*Ursus maritimus*) depend on sea ice as a platform from which to hunt their primary prey, ringed and bearded seals.

There is a strong seasonal component to the abundance of seabirds and whales. Piscivorous beluga whales (*Delphinapterus leucas*) spend part of the summer in the Chukchi Sea, although most migrate through the Chukchi to summering areas located to the east (Carroll et al., 1987; Moore et al., 1993, 2000). Similarly, bowhead whales, for the most part, migrate through the Chukchi Sea with little or no feeding in spring. However, both beluga and bowhead whales spend time feeding in the Chukchi Sea in late summer and fall (Clarke et al., 1993; Moore et al., 1995; Quakenbush et al., 2010). During the summer, species such as humpback (*Megaptera novaeangliae*), fin (*Balaenoptera physalus*), minke (*Baleanoptera acutorostrata*), and killer (*Orcinus orca*) whales also frequent the waters of the Bering Strait and Chukchi Sea, and some have also been observed on occasion in the Beaufort Sea (Reiser et al. 2009, Haley et al. 2009, Dickson 2011).

People inhabiting local communities are predominantly Inupiat and Siberian Yup'ik and populations vary from less than 5,000 (Barrow) to no year-round residents as, for example, King Island, a seasonally important location (Alaska Community Information Database). Marine resources are important as people live a subsistence-based lifestyle and derive much of their food from the sea. North Slope residents harvest (by weight) 61% marine mammals, 23% land mammals, 13% fish, 3% birds and eggs. Total annual harvest of wild foods is estimated to be 3.2 million pounds at 434 lbs. per capita, but subsistence harvest varies widely by community, year, and weather conditions, with a range known to span from 203 to 890 lbs. per capita. (ADF&G survey data.) Marine mammals such as the bowhead whale, several species of ice-associated seals, and walruses are important economically, culturally, and spiritually. They provide important sources of food, raw materials for transportation, clothing and art, and foci for passing down knowledge, hunting skills, and ways of life. Sea ice (timing, extent and thickness) dictates most of the interaction between people and their marine prey.

2. **Beaufort Sea Shelf**

East of Barrow Canyon is the Beaufort Sea with a shallow (<100 m) and narrow (50 to 100 km) interior shelf with a steep continental slope. It is further characterized by barrier island-lagoon systems extending along shore from the western Mackenzie Delta to the Colville River. The Beaufort shelf is a β-ocean that remains ice-covered throughout the winter, well mixed from fall through spring, and stratified in summer due warm (~4°C) freshwater input from the Colville and Mackenzie rivers, water intrusion from the clockwise flowing Beaufort Gyre, and wind and Gyre-induced upwelling of deep Atlantic Water.

Ice retreat in the Beaufort Sea occurs between June and August and is driven by solar radiation and heat advection from the Chukchi shelf, water emanating from the Mackenzie River discharge, and winds. The fresh and warm Alaska coastal current on the inner shelf is carried by the shelf-break jet, a surface-intensified current that originates north of Hanna Shoal. It is a primarily wind-driven surface current, with the predominant direction to the east that reaches to at least the eastern Alaskan Beaufort Sea, decreasing in speed along the way. Its presence is mainly seen during summer and autumn but may also reverse direction during upwelling events (which last a few days), typically in autumn.

Upwelled water along the slope provides nutrients and Arctic zooplankton species to both the Beaufort and—to a lesser extent—the Chukchi shelves. Upwelling events in the Beaufort Sea are powerful as they originate in storms associated with anomalies in the Aleutian Low position and strength. Primary and secondary production is low on the Beaufort shelf compared to the Chukchi, except in the west due to the influence of Barrow Canyon and along the retreating ice-edge. Zooplankton are comprised of species seasonally advected from the northern Bering / Chukchi system, large Arctic upwelled species, and small nearshore resident species. As such, their distribution and abundance is driven by a variety of different and seasonally-variable factors (predominantly upwelling and wind) that in turn influence the presence of their predators.

The spatial patterns of primary and secondary production are reflected in the decreasing trend of benthic biomass and species diversity from west to east and offshore to inshore. Epi-benthic organisms (such as snow crab, brittle stars, and crinoids) and fish predominate and are generally found in higher numbers along the shelf break. Fish biomass is dominated by eelpouts, sculpins, and sandlance on the benthos and Arctic cod in the water column. The infaunal community is mostly composed of bivalves, amphipods, polychaetes, and sipunculids. Anadromous Arctic cisco and chum salmon are native to the Mackenzie River and cisco migrate westward along the coast in a brackish corridor to the Colville River and back. Dolly Varden char occurs in this region as well, and several Pacific salmon species have also been recently detected.

Seabirds in the Beaufort depend on three different physical systems and feeding strategies. Piscivorous species such as black guillemots on Cooper Island depend mainly on Arctic cod and are thus heavily impacted by ice dynamics (Divoky pers. comm.). Planktivorous species such as short-tailed shearwaters are dependent on seasonal intrusion of zooplankton due to wind and upwelling patterns, whereas migrating ducks, loons, and shorebirds depend on the productivity in the shallow lagoons formed by the Barrier Islands and, thus, on processes controlling freshwater and sediment run-off from rivers.

Ringed seals den in snow on the sea ice in spring are the most abundant marine mammal in the Beaufort Sea and primary prey for polar bears. They are most common on the shelf break during the open water season where they feed on Arctic cod. Ribbon seals are less abundant but extremely vulnerable to changes in sea ice as they are ice-dependent during April-May when they haul out on the ice for pupping, nursing, and molting. Bearded seals are also present but prefer shallower waters where they feed on benthic infauna. Bowheads are the main whale species in the Beaufort, migrating through the area over the shelf between the Bering Sea and the Canadian Basin in spring and fall. Two apparently distinct populations of beluga whales exist in the Chukchi/Eastern Beaufort and western Beaufort Sea, respectively. They are piscivorous and prefer the shelf break environment. Most marine mammal species, with the exception of ringed seals and some bearded seals have migrated south into the Bering Sea by the fall.

The communities of Barrow (which is located where the Chukchi and the Beaufort Seas meet), Nuiqsut, and Kaktovik are the main communities along the U.S. Beaufort coast. Subsistence fishing (12%), sealing (7%), and whaling (57%) are an important part of the economic, nutritional, and cultural lifestyle of local residents. In winter, fishing has been traditionally conducted by gill nets threaded through holes in the ice or by jigging. In summer, rod and reel, gill net, and jigging are used to capture Pacific herring, Dolly Varden char, whitefishes, Arctic and saffron cod, and sculpins. Bowhead whales and bearded seals comprise the bulk of the marine mammal harvest. Marine mammal harvesting is strongly dependent on wind and ice conditions and is carried out by travelling across the ice with snow machines, or navigating on water with *Umiaks* (bearded seal skin kayaks) or small boats with outboard engines.

3. **Pacific Arctic Basin**

The Arctic Ocean is a bottom-up driven system that functions as a double estuary and is the largest heat sink for the planet as mid-latitude atmospheric and oceanic heat is transported northward (Serreze and Barry 2005). Waters entering the AO from the Atlantic Ocean and Bering Sea are transformed in its basin before leaving primarily through Fram Strait towards the Atlantic Ocean where they join the deep thermohaline circulation of the World Ocean, a key player in the planet's climate.

This water mass transformation is mainly driven by heat input, freshwater fluxes from river runoff, and precipitation, factors driven themselves by large atmospheric inter-decadal signals like the Artic Oscillation, the Arctic dipole, and the location of the Aleutian Low. The impact of these physical drivers is most easily represented by sea ice (which melts due to atmospheric and/or oceanic warming) and salinity. Sea ice and salinity, in turn, impact the three-dimensional circulation, ecosystem dynamics and composition (abundance and biodiversity), and hydrography of the entire Arctic Ocean (deep basin and shelves), and are key players with complex feedback mechanisms which typically tend to enhance large-scale and persistent warming anomalies.

The shelf waters of the Chukchi and Beaufort enter the deep Arctic Basin through different physical processes, e.g., canyon outflow, convection and associated downslope flows, eddy-induced mixing, and Ekman transport. Two currents dominate in the Pacific sector of the Basin: the clockwise-flowing, low-salinity Beaufort Gyre at the surface, and a deep anti-clockwise gyre beneath it with warm, high-salinity deep Atlantic Water. The water mass structure in the Basin typically presents a low-salinity mixed layer (0-25 m), a halocline layer (25-220 m), a thermocline layer (220-300 m), the Atlantic Water (300-500 m), and cold Arctic water from 500 m to the bottom. The halocline is created and maintained by river runoff and freshwater input through the Bering Strait and acts as a crucial barrier that shields the overlying sea ice from the underlying warm Atlantic water. Its dynamic depth also dictates how much interaction between the Atlantic and Shelf waters can take place through convection and ventilation processes that typically occur in winter and early spring.

Primary production in the Basin occurs mainly in the form of sea ice algae and ice edge phytoplankton blooms. It is thus heavily dependent on the presence and timing of retreat of sea ice. Basin production is generally lower than production over the shelves due to lower nutrient levels and short light and open water periods. Nutrients enter the system with water from the Atlantic, Pacific, and rivers, and are turned over in the winter through weak brine rejection convection. There are two resident copepod species (*Calanus hyperboreus and C. glacialis*) that occur in the Basin which, together with euphausiids, support ice-associated Artic cod. With almost no other pelagic consumers of primary and secondary production, most of the biomass sinks to the deep benthos at 640-3250 m depth, where polychaetes, crustaceans and mollusks dominate the biomass (Bluhm et al. 2004). There are likely some benthic fishes, but little is known about them. Recent findings suggest that ice, pelagic, and benthic systems are linked through sinking grazers and their products, rather than through direct input of algal material to the benthos (Bluhm et al. 2004, 2011).

Not much is known about the distribution and abundance of fish, birds, and mammals in the Basin. Arctic cod, at least to some extent, retreat over the Basin with the ice during summer and become key prey for ribbon and ringed seals who forage in deep water and who stay along the ice edge part of the year. Polar bears fall in that same category as they follow the ice and the seals. Belugas have also been reported off the shelf, and it is likely that some planktivorous seabirds roam the open waters and follow the ice edge over the Basin in the summer as well.

B. **Biological Hotspots**

Hotpots are areas of high biological activity and/or productivity that are present and stable at time scales of days to weeks (pelagic) or months to years (benthic). Hotspot formation and maintenance requires the presence of mechanisms that provide a continuous food source (nutrients, plankton) and are generally most closely associated with seasonal wind patterns and, more reliably with geographic features (straits, canyons) and associated topographically driven currents that create retention zones. Nearshore, hotpots are often associated with freshwater and sediment run-off areas.

Little is known about pelagic hotspots in this region with the exception of the ice edge, which moves in space and time, and two geographically stable areas: 1) some nearshore areas north of St. Lawrence Island where native hunters from Savoonga described large aggregations of seabirds, seals, and minke whales (Huntington et al. *in press*) and 2) the area around Barrow Canyon where hunters reliability find bowhead whales.

Other benthic hotspots include the area just north of Bering Strait, Barrow Canyon, Hanna Shoal, and the Barrier Island systems in the Chukchi and Beaufort Seas (Grebmeier 2012, Dunton et al. 2012). Most of the primary and secondary production that takes place over the Chukchi and Beaufort shelves and Arctic Basin is not consumed but exported out of the pelagic system to the benthos. Export rates, however, vary greatly by location, resulting in regional benthic hotspots. The ecological importance of the existence and location of hotspots varies by region and species. In the nearshore, these areas are key for migrating birds and fish, and the disappearance or shift in time of these highly productive areas would certainly have population-level impacts. Offshore, the location of benthic hotspots has shifted north over the last three decades (Grebmeier 2012), but region-wide hotspots clearly remain. These are predictably sought out by benthic feeders such walrus, even when sea ice in close proximity disappears, and they need to swim some distance from shore to reach them (C. Jay, pers. comm.). The sensitivity of consumer populations to predictable spatial hotspots is unclear.

C. **Key physical, biological, and human thematic drivers, linkages, and feedbacks**

Numerous positive (they enhance the initial forcing or perturbation) or negative (they weaken the initial forcing or perturbation) feedback processes are active in the Arctic. These processes may be atmospheric (water vapor, clouds, air temperature), oceanic components (salinity, nutrients, temperature, and current direction and speed), sea ice related (extent and thickness), and ecological. There are many uncertainties around how much each of these contributes to system change or how much they will change, but it is noteworthy that almost all of them are thought to enhance the current forcing or perturbation of the system (Francis et al. 2009). Many of these processes are nonlinear in nature, which makes it difficult to conceptualize them or to quantify and contrast their impact against those of other feedbacks with which they have at least one mechanism in common.

Atmospheric - Increasing atmospheric temperatures drive earlier sea-ice break-up and later freeze-up, lengthening the open water season and spatial extent, reducing albedo, which further accentuates atmospheric warming and increases heat influx into the water, thus further increasing sea ice melt from below, which in turn would intensify stratification. Increasing atmospheric temperatures further augment the volume and timing of freshwater and sediment influx (through melting glaciers and permafrost, increased precipitation, and earlier river melt) into the Arctic Ocean, influencing important nearshore habitats and species such as anadromous fish, as well as open ocean circulation and stratification patterns that are critical to controlling upwelling mechanisms on the Beaufort and Chukchi shelves.

Oceanic - Water masses create the connectivity among the Bering, Chukchi, Beaufort Seas, and the Arctic Basin. Sea level difference drives nutrient rich water northward through the Bering Strait. In early summer, when ice is receding, advection transports zooplankton from the southern Bering Sea into the Chukchi, through the Central, Barrow, and Herald canyons, and into the western Beaufort Sea and Arctic Basin, respectively. In this way, subarctic species of microzooplankton, copepods, and euphausiids seasonally intrude into the system, but—without adaptive mechanisms to survive the winter and few pelagic fish species to consume them—they eventually die and sink to the bottom. Seasonal primary production in the Chukchi is equally influenced by this influx of nutrients, as well as by the currents themselves which drive nutrient resuspension mechanisms from the rich benthos. Along the northern Chukchi and the entire Beaufort shelf, wind and Beaufort Gyre-induced upwelling also brings nutrients to the shelf and becomes seasonally important as one of the mechanisms that resets nutrients during the winter. It also brings some Arctic copepods onto the shelf, especially in the Beaufort, where they become important prey for migrating (summer and fall) bowhead and other whales and seasonally-present planktivorous seabirds. In late spring to early summer, vertical stratification increases due to atmospheric warming and river runoff, and water leaving the Chukchi shelf in summer is warmer, fresher, and depleted in nutrients but enriched in oxygen; the opposite occurs in the winter. These seasonal differences alter the eastward flowing current connecting the Chukchi and Beaufort, thus changing the potential for biological production seasonally.

Additional oceanic feedback results from the geostrophic and wind-driven currents which concentrate and retain exported biomass in and around topographical features such as canyons, straits, and shoals. These are particularly important on the Chukchi shelf and in the western Beaufort, where these hotspots create a rich benthic in- and epifauna that support benthic-feeding ducks, bearded seals, walrus, and gray whales during the open water season. Different mechanisms may operate on the central and eastern Beaufort shelf, which appears more dependent on ice edge blooms yet has a more developed pelagic food web and an observed decoupling of pelagic and benthic productivity. Most of the biomass in this system is composed of invertebrates, but some benthic fish and shellfish depend on this system. They are most abundant on the shelf edge and around hotspots, and have few adaptations to survive in the cold mixed waters in the winter. Some seem to overwinter in the sand (sandlance), but others migrate south into the Bering Sea (saffron cod, capelin) against the slow moving coastal current or into rivers and river deltas (cisco, Dolly Varden, chum). Others descend along the shelf slope into warmer deep Atlantic water (crab, eelpouts, sculpins, Arctic cod).

Sea Ice - Directly or indirectly seasonality and sea-ice dynamics (extent, thickness, timing of freezing and break-up), dominate the physical and biological dynamics in this region. Thus, anything that affects all or part of ice dynamics, from large scale atmospheric patterns influenced by atmospheric warming to local winds, has potentially wide-ranging impacts on the entire marine ecosystem. Ice-formation drives brine rejection convection important for nutrient mixing, especially off the shelf. Ice algae that grow in spring and summer comprise a significant amount of the primary production in these seasonal ice-covered regions (beta oceans), just as ice-edge blooms are key to prime open-ocean blooms in the summer and early fall, and the retreating ice-edge opens a highly productive estuarine-like nearshore corridor in which anadromous fish, marine fish, shorebirds, and other waterfowl flourish. As such, extent and timing determine when and where habitats open, blooms occur, when geostrophically and wind driven currents will advect nutrients and zooplankton into the system, when and where benthic hotspots will form and be maintained, and where nutrient resuspension can be a major contributor to the nutrient cycle.

Ecological - Timing, thickness, and extent of ice further influence the presence, distribution, and abundance of walrus and ice -associated seals, which are dependent on the ice (and snow in the case of ringed seals) for pupping, nursing, and molting in the spring (Apr-May), and often require ice dynamics to coincide with feeding areas to ensure breeding success and survival of juveniles and adults during summer. Polar bears depend on the abundance and distribution of ice-associated seals, in particular bearded and ringed seals, as their primary food source in the spring and summer and are additionally impacted by the presence of ice and snow in which they give birth and shelter their cubs. Several of the ice-associated seals are pelagic feeders and depend predominantly on Arctic cod, which as juveniles and sub-adults are ice-associated, but become increasingly benthic as they get older. This abundant keystone pelagic resource also feeds piscivorous seabirds and whales, and their spatial and temporal availability has been shown to impact the breeding success of black guillemots.

Because the entire temperature and ice-dependent system phenology drives the migration, location, and abundance of seabirds, seals, and whales, it also affects the health and culture of local residents. Inhabitants of the Arctic use the ice to travel on and hunt from and depend on these species as their primary food source. Hunting trips and camps are critical for cross-generational connectivity, cultural continuity, and information transfer. Several species of marine mammals such as bowhead whale and bearded seal play a key role in cultural festivals and many of the traditional artifacts still come from them. The North Slope Borough has raised billions of dollars for capital improvement projects by selling bonds that are retired by taxing Prudhoe Bay properties so that housing units, health and social services, life expectancy, telecommunications, job opportunities, airplane service, and barge traffic all have improved and increased over the last three decades. Despite these changes, native communities continue to rely on subsistence foods.

D. **Stressors and their ecological implications**

As noted already, the Artic marine ecosystem is influenced by a variety of large-scale stressors. The most obvious whose ongoing impacts have already been discussed is *climate change* in the form of *atmospheric warming*. Its cause is global in nature and is probably the most difficult to regulate as it needs to be addressed at a global policy scale. Atmospheric warming affects a variety of large-scale climate indices such as the Arctic Oscillation, the Arctic dipole, and the location of the Aleutian Low, all of which influence Artic circulation and sea-ice dynamics in a variety of ways. The effects of this stressor and its implications for sea-ice dynamics and the marine ecosystem as a whole are the most severe.

Increases in atmospheric carbon dioxide, are linked to *ocean acidification*. The Arctic Ocean is becoming undersaturated in aragonite, due to the high solubility of CO_2 in cold waters, melting sea ice, and increased upwelling of deeper and less $CaCO_3$-saturated water (Mathis et al., 2011; Yamamoto-Kawai et al., 2009). This chemical shift may lead to potential loss of organisms with aragonite skeletons/shells and physiological processes depending on the current carbonate chemistry of sea water, as well to impacts on their predators.

Another stressor frequently associated with oceans is *fishing* and other sources of *harvests*. On a federal level there is a moratorium on commercial fishing (NPFMC 2009), while at the state level there is a relatively small commercial salmon fishery in Kotzebue Sound and a small Dolly Varden char harvest in the Beaufort Sea. Subsistence harvests of fish, birds, and mammals are monitored and managed through a variety of regulatory laws and institutions, and generally presumed to have only a modest impact on ecosystem dynamics.

Contaminants, especially persistent organic pollutants (POPs), but also metal contaminants such as mercury and lead, are of further concern. They arrive into the marine system through atmospheric deposition from the south, through river discharges around the Arctic, from ocean currents entering the Arctic from Asia and Europe, and potentially from point sources related to industrial activities in the Arctic. POPs generally bioaccumulate and biomagnify in the Arctic food web and may reach concentrations that potentially interfere with a number of physiological processes (Muir et al., 1999, Trefry et al. 2008). Among the harmful organic contaminants are: methyl mercury, polybrominated diethylethers, organochlorines (chlordanes, hexachlorohexanes, PCBs and DDTs), and perfluoroalkyl compounds (Kelley et al., 2009; Muir et al., 1992).

While fear of contaminated foods has led to abandonment of traditional foods in some areas of the Arctic, it has also led to unhealthy food-habitats acquired from non-indigenous peoples (AMAP 2002).

Reduction in multiyear ice coverage has allowed a series of additional anthropogenic stressors to effect the Arctic. These include *oil and gas* exploration, development, and production in state and federal waters of the Chukchi and the Beaufort Seas, increased *shipping* in general, and other developmental activities. Driven by economic interests and national and global energy needs, the potential adverse effects associated with these activities include disruption of seabird and marine mammal migration routes, disruption of marine mammal foraging behavior (noise), spatial conflict with subsistence, release of contaminants, destruction of benthic or coastal habitat, and introduction of exotic or invasive species (via vessel traffic). Mitigation strategies and long-term monitoring programs are in place to address these potential impacts, but the possibility of a large marine oil spill and the technological limitations for cleanup remain an especially grave concern for all stakeholders.

Finally, we must consider cumulative and interactive effects. Marine organisms have some capacity to adapt to changing ocean conditions, but anthropogenic and natural influences such as those described above do not act in isolation, and together can exaggerate any single ecological or physiological stressor.

IV. The Recent Past

A. Physical

The greatest recent changes in the forcing of the Arctic Ocean over recent decades have been: 1) increased heat import via the atmosphere and through the flows entering the Arctic basin from the Atlantic and Pacific Oceans, and 2) increasing river runoff (freshwater and sediments), with the exception of glacier-fed streams and rivers that discharge on the Beaufort Sea (Dunton et al., 2012), which are decreasing.

The most visible and dramatic consequence of changes in physical forcing over the last three decades has been the reduction in summer sea ice extent and thickness. Both have a significant impact on the underlying ocean currents, stratification, biology, and people. Minimum summer ice extent is half of what it was in 1979, and its volume is 20%, indicating severe loss of multiyear ice throughout the Arctic Ocean. Ice melt has been occurring about 7 days per decade earlier in the Chukchi/Beaufort Seas (1980-2007), the fastest change in the entire AO (Markus et al. 2009), with a concomitant increase in the pace of ice melt of 10 days faster per decade (the average for the AO is 6.7 days per decade).

Other major physical changes include:

- Acceleration of the Beaufort Gyre (Proshutinsky et al. 2009) as well as a southeastward migration of its center,
- Change in the location of fronts, e.g., the Pacific/Atlantic front moving from the Lomonosov ridge to the Mendeleev ridge,
- Increased acceleration of the hydrological cycle and the increased input of freshwater from rivers is increasing salt stratification over the entire AO,
- Halocline depth in the Canadian Beaufort (in the area of the Beaufort Gyre) deepened about 30 m during 2002-2012 (Frey et al. 2012),
- Freshwater flux through Bering Strait increased between 1991 and 2008 concomitant with an overall increase in the volume transport and temperature (Woodgate and Aagaard 2005, Woodgate et al. 2010), and
- Winds at the Bering Strait show a slight trend toward weaker speeds. In the Canadian Beaufort, a weakening trend of the local wind speed between 1958 and 2008 was also found (Fissel et al. 2009). Re-analysis products show increasing winds over the Chukchi and Beaufort Seas (Hakinnen et al., 2008; Stegall & Zhang, 2012) and over the central Arctic basin (Spreen et al., 2011).

B. **Biological**

The few long-term datasets in the Arctic have shown significant variability and absolute change. Benthic biomass in the northern Bering Sea has been decreasing, while biomass of pelagic fish species is increasing; recent retrospective analyses suggest similar changes have occurred in the Chukchi Sea (Grebmeier et al 2006, Grebmeier and Dunton 2000). Benthic species composition is related to sediment size which in turn is influenced by current strength. The increasing flow through the Bering Strait may be changing benthic community assemblages and dynamics. With earlier break-up and a longer open water season, zooplankton are intruding farther into the Arctic and remain there longer (Ashjian 2013). Intensification of the Beaufort gyre and decreased ice cover have also increased wind mixing and wind-induced upwelling along the shelf, thus further increasing zooplankton presence (McLaughlin et al. 2011). The increase in zooplankton availability appears to be reflected in an increase in planktivorous seabirds in these shelf areas over the last 30 years (Gall 2013; B. Day, pers. comm.).

The species composition of the upper trophic levels appears to be to be shifting as sea ice cover has diminished. Ice-associated species are threatened by decoupling of feeding and rearing grounds (e.g., black guillemots, bearded seals, walruses, and polar bears), changes in prey availability (spotted, ribbon, and ringed seals), and diminished snow cover for denning (ringed seals and polar bears). At the same time, bowhead whale populations have increased, and southerly species (e.g., Steller sea lions, humpback and minke whales, orcas, salmon) are increasingly moving in to the region through the Bering Strait.

C. **Socio-economic and cultural**

Recent lease sales in the Chukchi Sea have dramatically increased exploration and research activities in this area and have raised concern in the local community about its impacts on the migration patterns and availability of marine mammals for subsistence harvest. Oil-based revenues, in aggregate, dramatically changed the structure and prosperity of the North Slope economy and continue to shape the direction of current social realities.

A synthesis of social indicator data collected from the North Slope Borough (NSB) population between 1970 and 2010 revealed the strong upward direction of several key trends, including growth in public services, human population, employment, household income, and subsistence activities. The NSB raises billions of dollars for capital improvement projects by selling bonds that are retired by taxing Prudhoe Bay properties. Health and social services increased such that life expectancy rose from 46 to 67. The median number of years of public education for young adults changed from <4 to >12. Satellite links have improved telecommunications while expanding airplane service and barge traffic have improved transport of goods and services, yet each community remains inaccessible by road.

Over the past forty years, the resident population of the NSB has increased from 3075 to 9472. In the 1970s, households resettled previously abandoned villages at Nuiqsut, Pt. Lay, and Atqasuk. Pronounced out-migration of young adults to urban areas also occurred, so that median age doubled from 17 to 35. Diversity also increased as non-Native residents grew from 17 to 41 percent, although they remain a minor fraction among both under-25 and over-50 age groups. In general, Inupiat households have become smaller, with mean household size reduced from six to three persons, with fewer extended family members. The employment numbers for all wage and salary jobs increased dramatically to 14,250, and females now constitute about half the workforce. The NSB remains the largest employer in the region, while the petroleum industry has directly employed only a small number of Natives. Unemployment rates remain typically higher outside Barrow. Median household income increased from about $34,000 to $77,000, while per capita personal income increased from <$15,000 to >$35,000. Yet, income disparity among Inupiat households has remained relatively stable. Since 1970, the percent of families with income below the federal poverty level has decreased from 28 to 11%.

Thawing permafrost and increased wind fetch has more than doubled erosion along the Beaufort Sea coast (Jones et al 2009), from historical levels of about 20 feet per year between the mid-1950s and late-1970s, to 28 feet per year between the late-1970s and early 2000s, to a rate of 45 feet per year between 2002 and 2007. Any increases in the current rates of coastal retreat will have further ramifications on Arctic landscapes —including losses in freshwater and terrestrial wildlife habitats and disappearing cultural sites, as well as adversely impacting coastal villages and towns.

D. **Traditional knowledge**

While scientific investigations of the Arctic Ocean are relatively few and recent, traditional knowledge (TK) of the region reaches back centuries and includes deep knowledge of physical and biological features. Application of traditional knowledge in scientific enterprises—such as ecosystem modeling—has increased in recent decades as its value has been more widely understood. Methods for integrating scientific and traditional knowledge have been described (Huntington 2000) and allow for a powerful synergy, especially when scales of observation are adequately considered (Gagnon and Berteaux 2009). Over the last ten years, government funded research has made notable progress in collecting TK and promoting a dialogue with external scientists on complex biological topics (Huntington et al. 2004; Ozeeva et al. 2004; Williams 2012). Other common channels for TK integration include government-to-government consultations with tribal leaders and councils, and NEPA processes that allow for public testimony.

V. The Future

A. **Lessons learned from the Paleontological record**

Current and projected change in the Arctic must be understood in the context of past changes in glaciation, sea level, and human settlements. There is no exact match in the paleontological records for the present physical state of the Arctic system; anthropogenic forcing is driving warming one hundred times faster than any change in the paleontological record. For example, haloclines presently are significantly shallower than those estimated for the last glacial period in which the Atlantic Water was too deep to effectively clear the sill depth (at the Greenland-Scotland ridge) when entering the AO.

Recent studies showed that bowhead whale, for example were present in the Pleistocene, but shifted their range by tracking suitable habitat (ice) northwards during the rapid climate change of the Pleistocene–Holocene transition (Foote et al. 2013). Overall, however, there is little information about past ecosystem structure and function, except that food must have been sufficiently abundant to support a small human population.

The Beaufort Sea coasts were populated about 30,000 years ago by migrating aboriginal peoples from Siberia. Around 9,000 years ago they were replaced by Indians, and then 4,000 years ago by Paleo-Eskimos such as the Dorset culture. This culture flourished for about 1500 years, with adaptations to a colder climate that included winter hunting of marine mammals on sea ice and fishing (bones of Arctic char were found at the 4,000-year old settlements). By about 1200 years ago, a warming phase extended the open water season and reduced hunter access to marine wildlife probably leading to the observed decline in the human population. The Dorset tradition was displaced by the Thule tradition about 1000 years ago. Innovations by the Thule included hunting large sea mammals in open water with the aid of drag floats attached to a harpoon line, large skin boats, the use of dogs to pull large sleds, and construction of multi-family subterranean houses that allowed winter storage of surplus bowhead whale meat. The earliest Thule sites occur in the Bering Strait and reveal nearly complete reliance on marine resources, although later sites reveal complementary use of terrestrial resources. The terms Inuit and Eskimo (Inupiat and Yupik) are contemporary labels applied to modern descendants of these ice-adapted populations. During the "Little Ice Age" (350 to 150 years ago), the Arctic climate cooled dramatically. Increased sea ice kept large whales from entering Arctic waters and forced hunters to change their way of life. Large numbers of the population abandoned permanent coastal houses for snow-houses on the ice where they could capture seals at their breathing holes.

Thus, adaptive response to a fluctuating environment has always been the key to human survival in Arctic Alaska. Native subsistence activities have historically thrived across centuries of change by virtue of constant innovation and experimentation, which would lead us to believe that they have the potential to continue to do so in the future.

B. Future Issues to consider

Paleontological records, scientific observations and traditional knowledge suggest that the Arctic is trending toward a state not seen before. The region is rapidly warming and continued changes in sea ice, ocean chemistry, and marine ecosystems structure and function are unfolding. Current Arctic ecosystems have evolved in response to frigid temperatures and short, cool growing seasons. As a result, climate change will impact short-term effects and variability in both the physical (e.g., wind, waves, currents, temperature, stratification, nutrients, precipitation, and freshwater input) and the biological (e.g., productivity, food availability, and reproduction) characteristics of the system, as well as drive longer-term ecological changes (e.g., temperature regimes and shifts in species distributions) and impacts on local cultures and communities.

1. Potential Drivers and Stressors

Temperature: The Arctic is one of the fastest warming regions on earth, as is evident in modern day Alaska (IPCC 2007, ACIA 2004, Holland and Bitz 2003; NCA 2012). The U.S. Arctic has seen general warming in all seasons over the last decade and more so than lower latitudes because of positive feedbacks involving albedo and ocean heat storage. Alaska's average annual statewide temperatures during the past 60 years have increased by nearly 4°F. The U.S. Arctic's near-term climate through 2030 will likely be dominated by a 1.5-2° C increase. Further into the future, 2070-2099, temperature increases from 4 to 22°F are predicted, depending on which fossil fuel emissions scenario is used. Decadal mean temperatures will consistently be warmer than those experienced in the late 20th century. In general, trends point toward increased minimum temperatures and fewer extreme cold days (Alaska Climate Research Center 2012).

Sea ice: Arctic-wide, the extent of sea ice in September is projected to decrease between 39% and 94% by 2081-2100 compared to 1986-2005 (IPCC 2007). Over the next three decades, sea ice is projected to be extensive in winter until May, but the timing and extent of sea ice in the Chukchi Sea will trend towards sea ice-free conditions into November each year with ocean temperatures above freezing. This ice-free region will absorb solar radiation rather than reflecting the sunlight off of sea ice as in previous decades. A positive feedback between the loss of sea ice and warming of the Arctic Ocean through absorption of solar radiation is amplifying the trends and generating more intense summer storms north of Alaska. This "new normal" makes it unlikely that the U.S. Arctic climate will return to previous conditions in the coming decades. Sea ice models consistently predict a nearly ice-free summer within the next 20-30 years with a remnant of ice possibly persisting in the Canadian Archipelago and along NW Greenland. The implications of decreasing sea ice include: altered global climate patterns, an increase in the occurrence of high-latitude fires, increased ocean acidity, and changes in the productivity (and its phenology) of marine ecosystems (Wieslaw and Roberts 2010, Serreze and Francis 2006, Holland and Bitz 2003, Overland et al. 2012, Slagstad et al. 2011, Wassmann et al. 2011, Yamamoto-Kawai et al. 2009, Hu et al. 2010).

Ocean acidification: Ocean acidification will likely have consequences for the entire Arctic marine ecosystem (Yamamoto-Kawai et al. 2009). By 2020, the ocean may be too corrosive for calcifying organisms to persist. Decreased shell production and other key biological processes have the potential for a system-wide reorganization of the marine ecosystem (Orr et al. 2005, Grebmeier 2012).

Currents and Winds: Recent trends show an increased acceleration of the Beaufort Gyre and of the eastward coastal current on the northern Alaskan shelf. The result would be an increased horizontal shear offshore of the Beaufort (and to some extent the eastern Chukchi) Sea shelf. This increased shear will favor the formation of baroclinic and barotropic instabilities. This dynamic contrast off the shelf would also tend to develop a stronger front in this area, which would tend to isolate the shelf from advective exchanges with the offshore ocean to the north. On the contrary, the instabilities could also increase this onshelf-offshelf exchange of properties due to increased horizontal mixing. In addition, ice melt and increased freshwater run-off will move the system towards an increased stratification, fresher surface layers, and shallower haloclines (McLaughlin et al. 2009).

2. **Potential ecological effects**

With warming and changing sea ice conditions, shifts in the distribution of marine fish from south to north are expected and are probably occurring already. More favorable conditions for Arctic fish species, such as Arctic cod larvae and saffron cod, are expected (Grebmeier et al., 2006). Some species of salmon (pink, chum) and cold-tolerant snow crab may increase in abundance in the Alaskan Arctic (Hollowed et al., 2012). Colonization by other salmon species (chinook, sockeye, coho) not already established there will depend on their ability to successfully spawn in perennial spring habitats located in drainages in the Alaska Brooks Range.

A northward migration of the current groundfish fishery in the Bering Sea is not anticipated over the next few decades (Sigler et al. 2011). Seasonal ice cover and cold (< 2°C) bottom waters on the Bering shelf form a barrier to the northward migration of subarctic bottom fish species typical of the southeastern Bering Sea, such as pollock and cod. Finally, a combination of warmer surface water, loss of sea ice, and ocean acidification may adversely affect development and productivity of some species or that of their natural predators (Fabry et al. 2008, Cooley and Doney 2009). Food web impacts would propagate through the system, from benthic organisms to their predators, and, ultimately, subsistence users. Ice-associated species (e.g., ringed seals and bowhead whales) may be largely or completely replaced with open-water competitors (e.g., harbor seals and humpback whales) that may or may not be suitable substitutes for subsistence harvesting.

In the northern Bering Sea, energy flow has shifted from the benthos to the pelagic zone, in part due to range extensions into northern waters by pelagic fish (Grebmeier et al. 2006b). Finally, less ice and more open water may lead to increased human activities, including oil exploration, shipping, and commercial fishing.

3. **Potential socio-cultural-economic effects**

New challenges for the inhabitants of Arctic Alaska can be anticipated on two pivotal fronts: economic transition and climate change (Williams in press). National policies promote active oil and gas leasing/permitting, exploration, and development on the North Slope and offshore. With such pressure for growth, local communities remain highly challenged in their efforts to maintain some control over the magnitude and pace of future development. On the other hand, declining oil revenues may yet lead to some of the most significant community impacts. As large oil fields age and the assessed valuation of petroleum facilities depreciate, tax revenues and the bonding capacity of the North Slope Borough also declines. The current way of life that is supported by oil revenues will be difficult to maintain if funding from these revenues diminishes public services.

Climate change will produce physical impacts on villages, such as erosion, subsidence, floods, and storm surges. Those stressors will require emergency responses, infrastructure investments, and in some cases even full-scale community relocation. Climate change will further reduce sea ice extent and thickness, with diminished hunter access to ice-dependent species and substantially increased operational dangers. Wainwright hunters already report fewer days available when weather conditions permit safe pursuit of whales. Such trends will likely increase hunting pressure on terrestrial wildlife and lead to increased competition and spatial use conflicts among hunters as well as diverse stakeholder groups. The increased competition and danger will likely spur new capital expenditures and increase local dependence on costly fuel, with corresponding increases in social stratification and fragmentation. Warming temperatures will change wildlife foraging behaviors, with negative implications for subsistence harvest efficiency. Diminished hunter access and harvest efficiency could undermine cultural transmission to youth. Perceptions of substantial environmental discontinuities may lead to reduced authority of elders and could undermine confidence in traditional knowledge.

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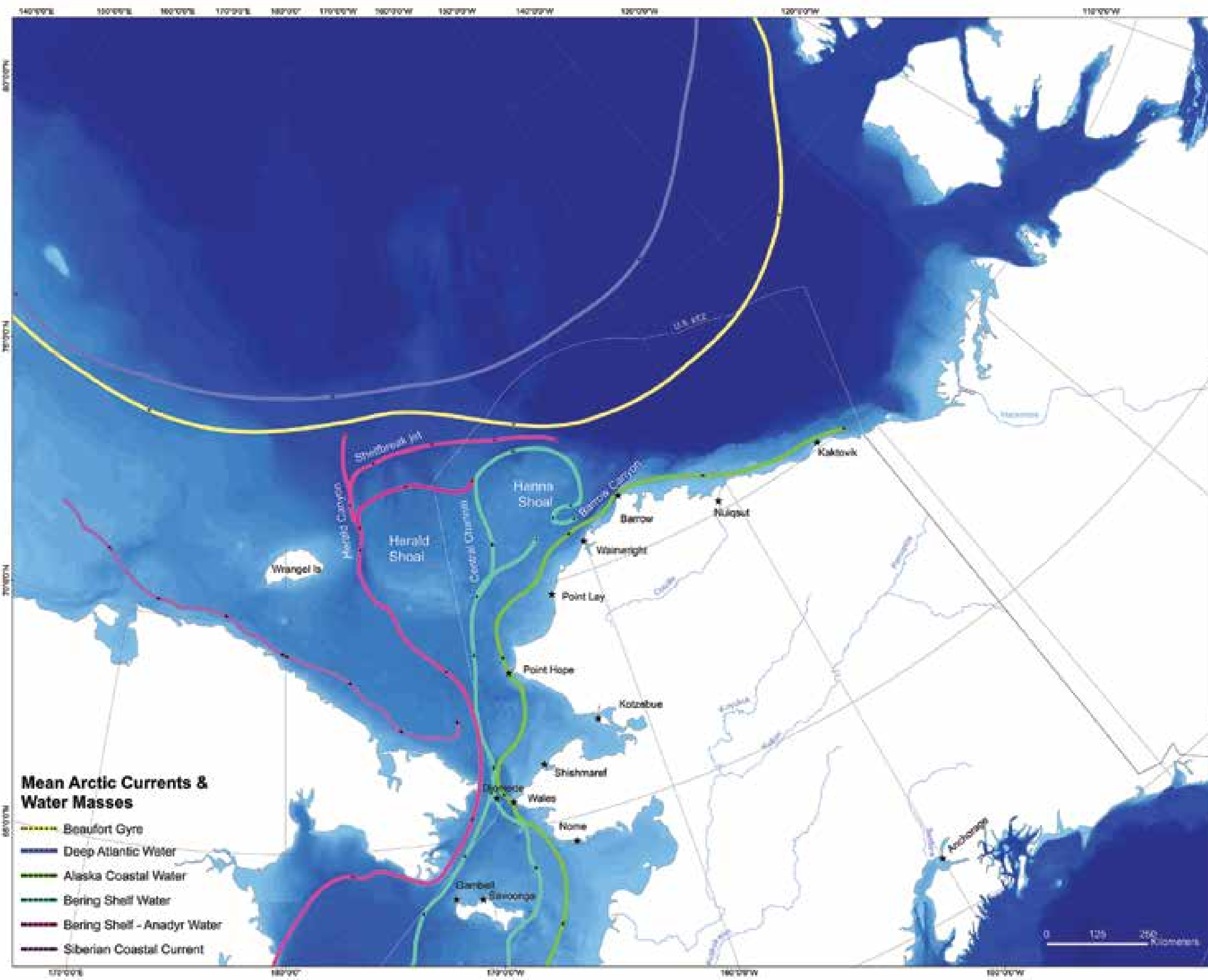

Fig 1: The Northern Bering, Chukchi, and Beaufort Seas study area.

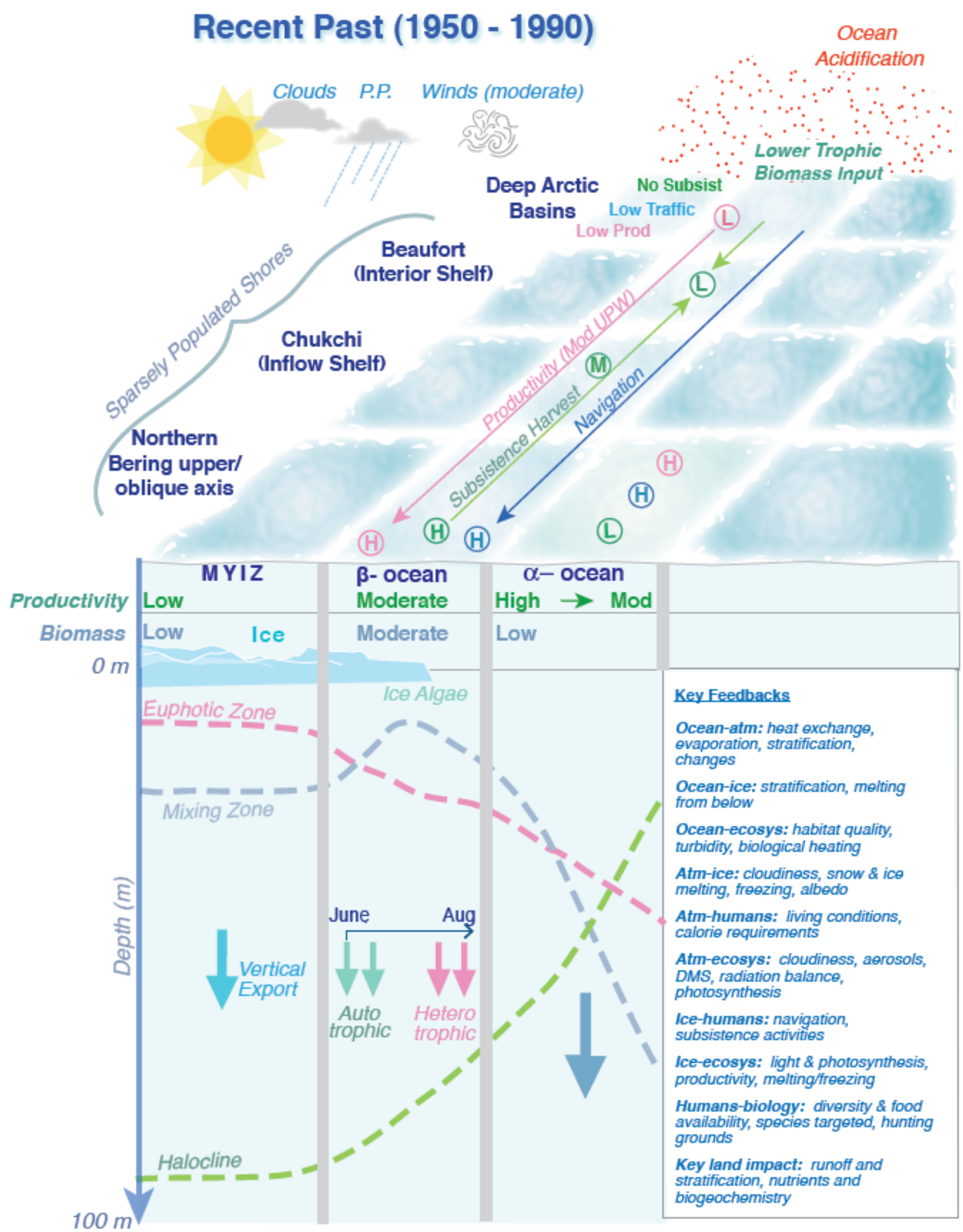

FIG 2: Physical condition-based approach for study area (adapted from Carmack and Wassman (2006). Conditions shown are those for the recent past (1950-1990). The figure shows shelf type (oblique axis), vs. ocean type (horizontal axis) vs. depth (vertical axis). MIY refers to multiyear ice, a beta-ocean refers to an ocean characterized by a seasonal sea ice coverage and a salinity dominated stratification, an alfa5ocean symbolizes oceans with no sea ice and a temperature dominated stratification. Note: the southern Bering Sea is represented here for the sake of completeness but it's not discussed in the text as it is outside the scope of this document. Ocean acidification is represented by a cloud of red dots near the surface (with different density in both figures). The width of the columns indicates the relative size difference of these different ocean types in the region of interest. Feedbacks considered to be most relevant during the indicated time period are listed.

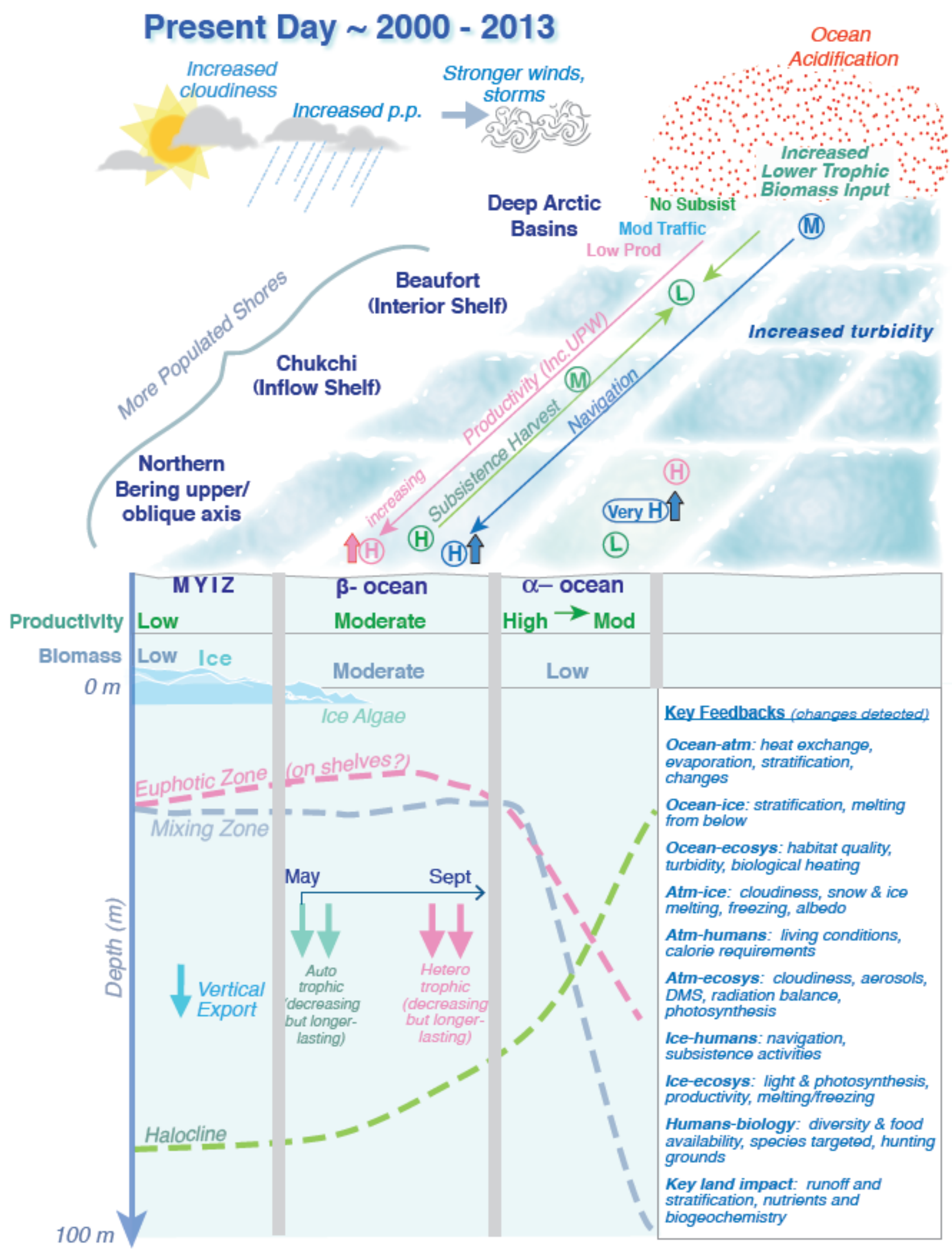

FIG 3: Trophic/based framework for the PRESENT northern Bering and Chukchi Seas. Size of boxes is not indicative of scale. Directionality of arrows indicate energy flow and width presents relative contributions (exception are orange arrows which are not to scale and indicate physical forcing). Purple shading, ovals and arrows represents pathways and species that are sea icedependent. Orange boxes represents all other physical drivers. Green and blue shading represent the benthic and pelagic systems and pathways, respectively. Turquoise shading and arrows represents groups and pathways that have both a benthic and a pelagic link. Dark gray box represents biomass export to the benthos from primary and secondary producers. Light gray boxes and arrows and thought to be currently absent from the system. The arrow with 'rates' indicates the direct influence of temperature on growth and feeding rates. Dashed boxes and arrows indicate elements that are mostly driven by factors dictating seasonal intrusion or species migration, whereas as components and their associated pathways that are considered 'resident' species are shown with solid lines. This is meant to show which parts of the ecosystem and pathways (other than the obvious physical ones) are dependent on outside processes.

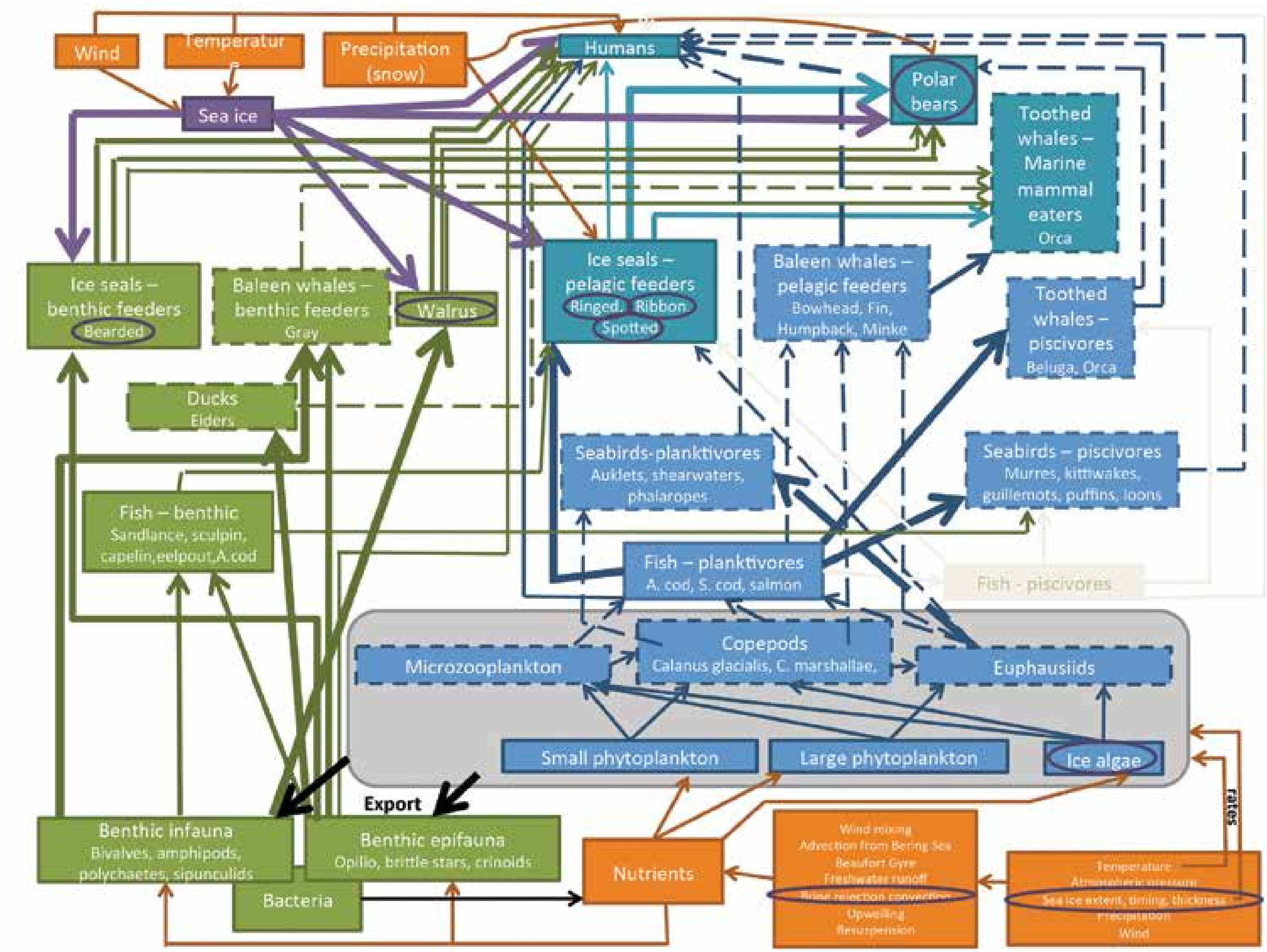

FIG 4: Trophic/based framework for the PRESENT northern Bering and Chukchi Seas. Size of boxes is not indicative of scale. Directionality of arrows indicate energy flow and width presents relative contributions (exception are orange arrows which are not to scale and indicate physical forcing). Purple shading, ovals and arrows represents pathways and species that are sea ice/dependent. Orange boxes represents all other physical drivers. Green and blue shading represent the benthic andpelagic systems and pathways, respectively. Turquoise shading and arrows represents groups and pathways that have both a benthic and a pelagic link. Dark gray box represents biomass export to the benthos from primary and secondary producers. Light gray boxes and arrows and thought to be currently absent from the system. The arrow with 'rates' indicates the direct influence of temperature on growth and feeding rates. Dashed boxes and arrows indicate elements that are mostly driven by factors dictating seasonal intrusion or species migration, whereas as components and their associated pathways that are considered 'resident' species are shown with solid lines. This is meant to show which parts of the ecosystem and pathways (other than the obvious physical ones) are dependent on outside processes.

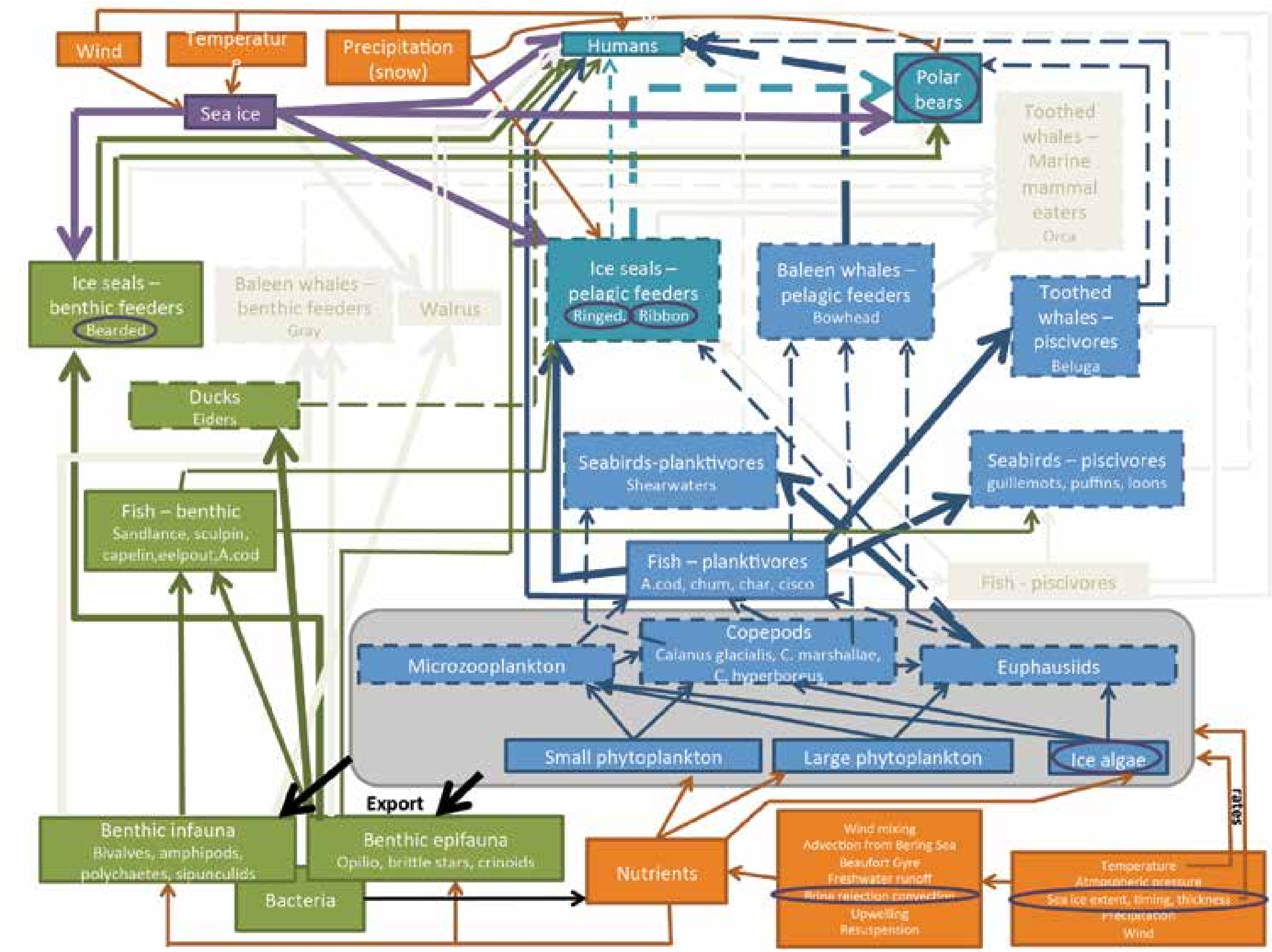

FIG 5: Trophic/based framework for the PRESENT Beaufort Sea. Size of boxes is not indicative of scale. Directionality of arrows indicate energy flow and width presents relative contributions (exception are orange arrows which are not to scale and indicate physical forcing). Purple shading, ovals and arrows represents pathways and species that are sea ice/dependent. Orange boxes represents all other physical drivers. Green and blue shading represent the benthic and pelagic systems and pathways, respectively. Turquoise shading and arrows represents groups and pathways that have both a benthic and a pelagic link. Dark gray box represents biomass export to the benthos from primary and secondary producers. Light gray boxes and arrows and thought to be currently absent from the system. The arrow with 'rates' indicates the direct influence of temperature on growth and feeding rates. Dashed boxes and arrows indicate elements that are mostly driven by factors dictating seasonal intrusion or species migration, whereas as components and their associated pathways that are considered 'resident' species are shown with solid lines. This is meant to show which parts of the ecosystem and pathways (other than the obvious physical ones) are dependent on outside processes.

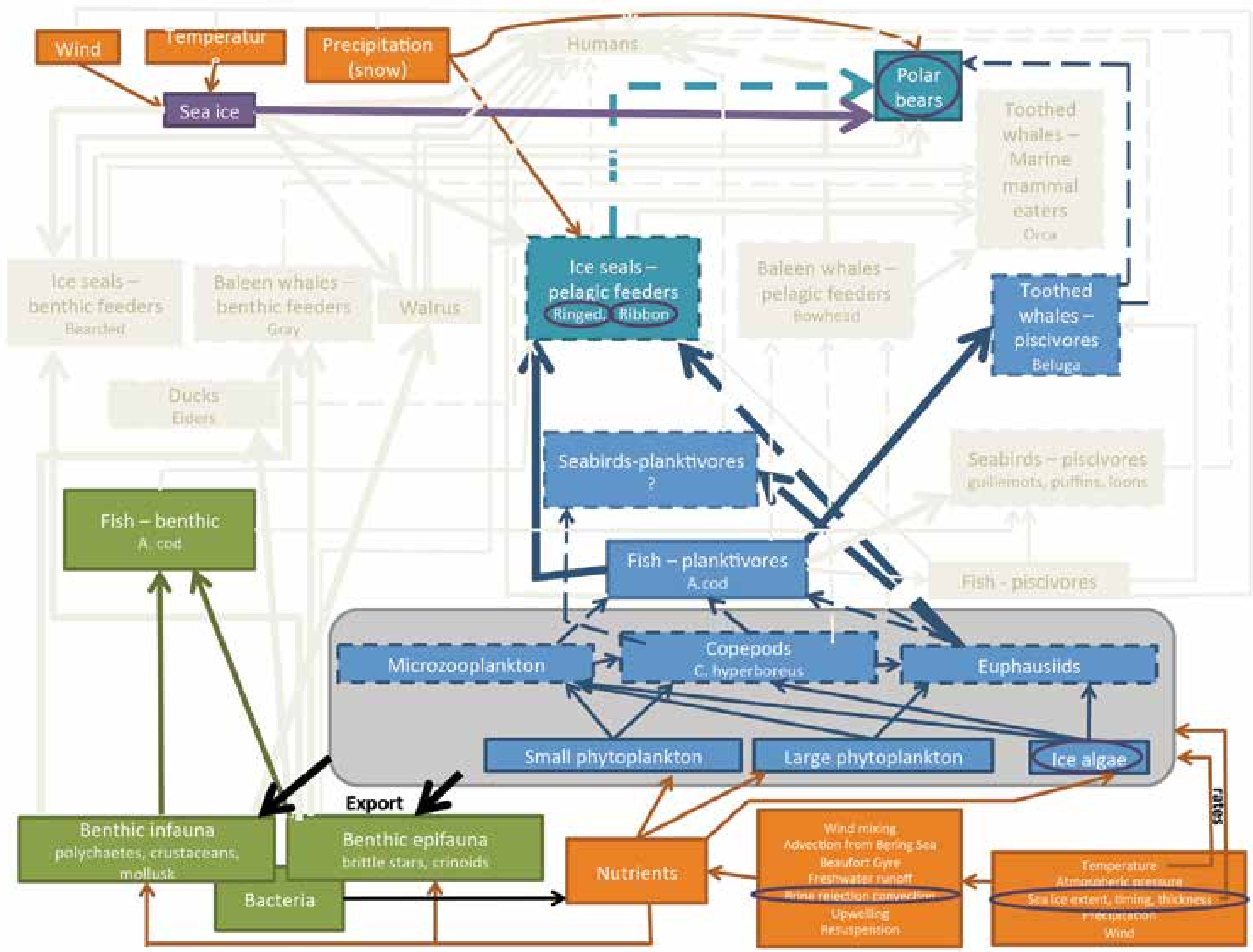

FIG 6: Trophic/based framework for the PRESENT Pacific Arctic Basin. Size of boxes is not indicative of scale. Directionality of arrows indicate energy flow and width presents relative contributions (exception are orange arrows which are not to scale and indicate physical forcing). Purple shading, ovals and arrows represents pathways and species that are sea ice/dependent. Orange boxes represents all other physical drivers. Green and blue shading represent the benthic and pelagic systems and pathways, respectively. Turquoise shading and arrows represents groups and pathways that have both a benthic and a pelagic link. Dark gray box represents biomass export to the benthos from primary and secondary producers. Light gray boxes and arrows and thought to be currently absent from the system. The arrow with 'rates' indicates the direct influence of temperature on growth and feeding rates. Dashed boxes and arrows indicate elements that are mostly driven by factors dictating seasonal intrusion or species migration, whereas as components and their associated pathways that are considered 'resident' species are shown with solid lines. This is meant to show which parts of the ecosystem and pathways (other than the obvious physical ones) are dependent on outside processes.

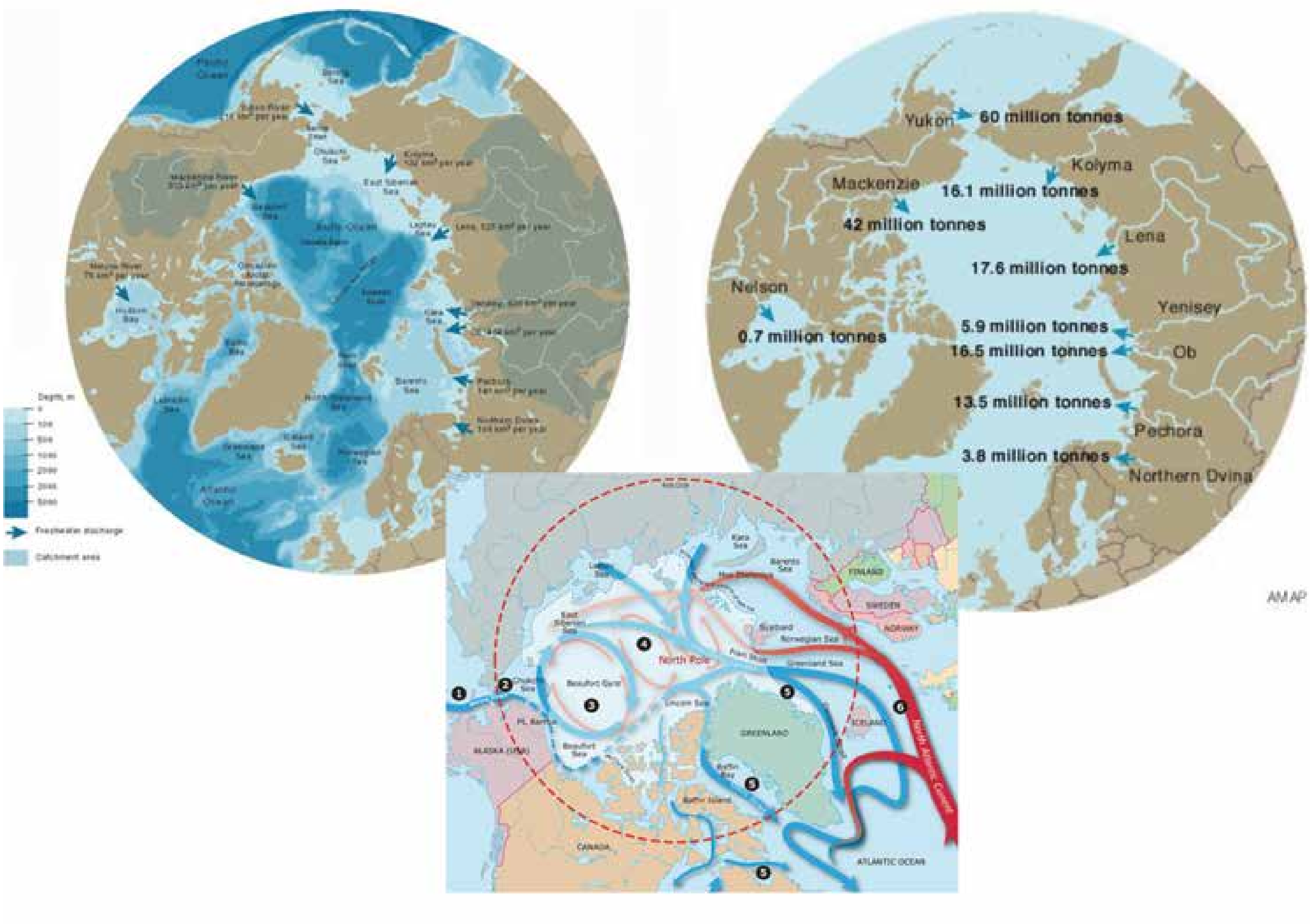

FIG 7: Major currents, freshwater and sediment input into the Arctic Ocean.

APPENDIX C
Summary Papers by Subject-Area Experts

Physical Drivers of the Chukchi, Beaufort, and Northern Bering Seas
R.S. Pickart, G.W.K. Moore, T.J. Weingartner, S.L. Danielson, and K.E. Frey

Biological Oceanography of the Arctic Ocean
Gradinger, R.

Benthos in the Pacific Arctic Region
Bluhm, B.A., J.M. Grebmeier, and K. Iken

Fishes of the Chukchi and Beaufort Seas
Norcross, B.

Seabirds
Springer, A.

Biological Hotspots in the Pacific Arctic: Physical drivers, ecosystem productivity and sensitivity to climate change
Grebmeier, J.M., L.W. Cooper, K.E. Frey, S.E. Moore, and R.S. Pickart

The Impact of Anthropogenic Activities in the Changing Arctic Ocean
Spies, R. and S. Senner

Development of a conceptual model of the Arctic Ocean ecosystem
Gibson, G.

Ecosystem services, socioeconomics, and impacts of change on local communities
Behe, C. and R. Daniel

Physical Drivers of the Chukchi, Beaufort, and Northern Bering Seas

R.S. Pickart, G.W.K. Moore, T.J. Weingartner, S.L. Danielson, K.E. Frey

Introduction and Basic Circulation

This white paper briefly summarizes the different mechanisms that together dictate the physical state and variability of the Chukchi, Beaufort, and northern Bering Seas. Many of these physical drivers directly impact the broader ecosystem, but such links are not discussed explicitly here. We focus predominantly on the Chukchi and Beaufort Seas, and address the northern Bering Sea as a boundary condition for the two northern seas. The Bering Strait is the sole connection between the Pacific and Arctic oceans (Fig 1). The Strait transport is northward on average, driven by the steric height difference between the Pacific and Atlantic Oceans. The northward flow is an important source of nutrients, carbon, heat (in summer and fall), freshwater, and halocline source water.[1,2] North of the Strait the Pacific Water flows as three branches, dictated largely by the bathymetry of the Chukchi shelf. Herald and Barrow Canyons help funnel the water northward on the two sides of the shelf,[3,4,5] and the Central Channel steers water towards Hanna Shoal[4,5]. Much of the water in the central and eastern pathways ends up flowing through Barrow Canyon. In the absence of strong winds, a significant portion of the Pacific water forms an eastward-flowing shelfbreak jet along the northern edge of both the Chukchi and Beaufort Seas[6,7] (Fig. 1).

Atmospheric Forcing

Winds. The meteorology of the region is largely dictated by two centers of action: the Beaufort High (BH) and Aleutian Low (AL). The BH is most pronounced in summer, though in some years its anti-cyclonic circulation is replaced by a cyclonic regime.[8] The AL represents the integrated impact of cyclonic low pressure systems transiting from the northeast coast of Asia to the Gulf of Alaska and is most intense during the fall and winter months.[9] Upwelling occurs frequently along the Beaufort slope and northeast Chukchi Sea driven by easterly winds that result from the interplay between the two centers of action. While short-term fluctuations of the BH can induce upwelling,[10] it is more common that transient Aleutian Lows migrate far enough north to influence the region. Upwelling is most common in fall,[11] while upper-level atmospheric blocking patterns often keep the AL storm trajectories to the south in winter.[12]

Buoyancy Fluxes. Averaged over the region of interest, the 2 m air temperature ranges from -20^{o}C in winter to 3^{o}C in summer, according to the North American Regional Reanalysis (NARR, 1979-2012). Monthly-mean autumn heat fluxes over the open water, as large as 80 W/m^2, lead to freeze-up, and re-freezing occurs within the leads and polynyas that periodically open up in the Chukchi Sea during winter (the NARR fields do not accurately capture such small-scale features). In summer, heat fluxes of the same order of magnitude, but oppositely signed, result in ocean warming. E-P undergoes a change in sign from monthly summer values on the order of -0.5 mm/day to winter values near 0.2 mm/day.

Lateral Influences

Bering Strait. Both the transport and water properties passing through the Bering Strait are time-varying and a consequence of processes occurring over the Bering Sea basin and shelf. These include wind-forced upwelling of moderately saline and nutrient-rich waters from the basin primarily through the Gulf of Anadyr; wintertime formation of near-freezing, salty halocline source waters in the polynyas and leads of the northern Bering Sea shelf; the influx of low-salinity waters from the Gulf of Alaska shelf; and regional river runoff. These various water masses are, to some extent, mixed with one another over the northern Bering and southern Chukchi shelves. Each of these processes, including mixing, is modulated by the strength and position of the Aleutian Low. To zeroth order, the seasonal water mass properties of the Chukchi and Western Beaufort Seas are dictated by the flow through Bering Strait.[5]

Shelf edge. Both the Chukchi and Beaufort Seas experience extensive shelf-basin exchange that is internally and externally forced. Easterly winds drive surface water offshore and halocline waters onto the shelf. In summer and fall this results in significant fluxes of heat and freshwater to the basin and a net flux of nutrients onto the shelf.[13] Westerly winds transfer near-bottom shelf waters to the basin. In the absence of winds, the seasonally varying shelfbreak current is baroclinically unstable and regularly spawns eddies that carry shelf properties into the basin.[14,15]

Sea Ice

The Chukchi and Beaufort Seas are typically ice covered in winter and partly to mostly ice-free for part of summer/fall. Land-fast ice covers the inner Beaufort shelf from fall to spring. Freeze-up is a relatively synoptic process that occurs from late-November through mid-December, whereas spring breakup is typically a longer process that progresses from May–July throughout the region. Seasonal melt-back during spring occurs first along the three Pacific Water flow branches (Fig 1) owing to the advection of heat from the Bering Sea.[3,16] The pack-ice is very dynamic throughout the winter season. Polynyas regularly form in the vicinity of Wrangel Island, along the Siberian coast, and in the northeast Chukchi Sea between Cape Lisburne and Barrow Canyon.[17] The northeast Chukchi polynya influences the density of the Pacific winter water that ventilates the upper halocline via Barrow Canyon,[18,19] while the Wrangel Island polynya does the same for winter water draining through Herald Canyon.[20]

Anticipated Changes over the Next Several Decades

A strong trend in annual sea-ice persistence has already occurred over the past few decades, due to earlier melt-back as well as later freeze-up.[21] This is most pronounced on the outer Chukchi and Beaufort shelves. Consequently, the sea surface temperature has increased considerably in summer/fall[22] and subsurface water masses on the Chukchi shelf have warmed in spring. This trend will likely accelerate in the future. Based in part on observed trends in the NARR fields, anticipated future changes associated with the atmospheric forcing include: warmer air temperatures (particularly in summer and fall); larger negative air-sea heat fluxes in summer (ocean warming) peaking earlier in the season, and larger positive air-sea heat fluxes in autumn (ocean cooling) peaking later in the season; more frequent and stronger storms, including Arctic-born storms that cause erosion on the North Slope; an intensification of the E-P summer-winter dipole; and a stronger BH. As a result of these many changes, the wind-driven variability in the Chukchi and Beaufort Seas will become enhanced (stronger winds, less damping due to ice), and shelf-basin exchange via upwelling and downwelling will increase. Melt ponds will become more extensive, and near-surface stratification will increase. In terms of lateral inputs, the inflow through Bering Strait will likely become warmer and fresher, and, because of the accelerated hydrological cycle at lower latitudes,[23] the volume transport may change (driven by changes in the Pacific-Atlantic steric height difference). The riverine input will increase because of the wetter/warmer conditions, and the spring discharge will occur earlier and last longer. Groundwater/salinity transport to the shelves should also increase. An important far-field ramification of the changes on the Chukchi shelf is that the halocline of the Canada Basin will likely be ventilated at a warmer temperature.

Key Knowledge Gaps

Presently there are many aspects of the physical drivers in the Chukchi/Beaufort Seas that are inadequately understood. These include, but are not limited to: the relative roles of the Bering Strait heat fluxes, winds, cloudiness, and air-sea heat exchange in the seasonal advance/retreat of ice over the Chukchi shelf; the complex flow patterns on the outer-shelf (particularly near Hanna Shoal and the shelfbreak); the dynamics and fate of the outflow from Barrow and Herald Canyons (especially the role of turbulent processes); the lateral connection between the East Siberian and Chukchi shelves, including the dense water emanating from the Wrangel Island polynya and the buoyant flow of the intermittent Siberian Coastal Current; the wind-driven response on the Chukchi shelf and shelfbreak in the presence of different ice configurations (particularly the downwelling); and the mixing of different water masses on the shelf and the associated local modification of Pacific Waters.

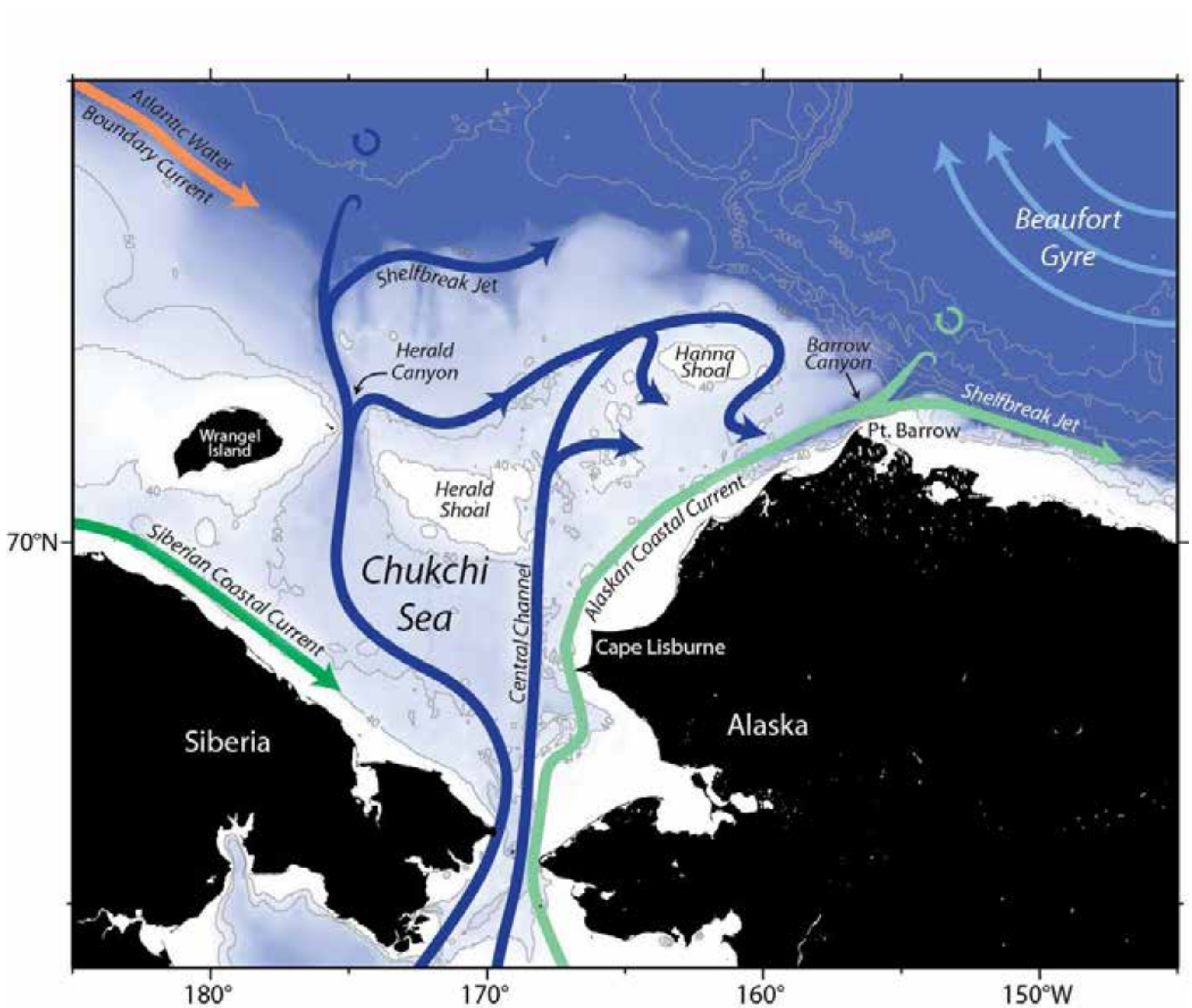

FIG 1: Schematic of the major currents in the Chukchi Sea.

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Whitepaper Biological Oceanography, Arctic Ocean

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Several unique environmental factors are shaping the biological processes in the mediterranean Arctic Seas. Those include seasonality of light, temperature, freshwater input, presence of ice and inflow and outflow from sub-Arctic Seas. Several of these factors are predicted to change in the very near future or are currently already in the process of reaching a new equilibrium. A central question is, given all the ongoing and predicted changes – will the Arctic Ocean biology pass tipping points reaching a new equilibrium that we are not familiar with. For example: Could jellyfish be the main plankton taxa similar to events in the Bering Sea? Will changes to sub-Arctic species communities change the food quality for higher trophic levels providing less quality food with less energy content? This will be a specific challenge for modeling efforts as we might need to include species which are currently either not in the system or ignored in current ecosystem models because of low abundance. I will first outline some of the unique characteristics, followed by some relevant changes and third looking at gaps in knowledge and specific research needs.

Seasonality:

Any Arctic biological system is highly pulsed. In the high Arctic no primary production may occur for over five months every year, followed by weeks of very intense algal blooms and high zooplankton grazing and – on the shelves – very high vertical input into the benthic systems. In nutrient rich regions (Bering/Chukchi) total annual production can exceed 300gC m^{-2}, among the highest marine values on earth, sustaining high pelagic and benthic faunal biomass and production. Substantial remineralization on the shelves release ammonia which can be important nutrient source for algal production. Annamox is reported from various arctic shelves. Algal blooms can be advected off the shelves and contribute to slope and deep sea pelagic and benthic food webs.

Future changes: no changes in the seasonality of light, however changes in the epipelagic nutrient regime (rate of upwelling, flow rates through Bering Strait or Fram Strait or Barents Shelf) will either increase or decrease annual production. Scientific arguments for both increase and decrease scenarios exist.

Sea ice:

Sea ice currently exists for several months to year-round in the Arctic both as pack ice and as land fast ice. Sea ice harbors over 1000 algal species, over 30 metazoan taxa and an unknown number of viruses and bacteria. Some species are ice endemic in the central Arctic. Ice algal production contributes about 4% (on shelves) to about 55% (central Arctic) to total primary production. In spring ice algal blooms occur months before pelagic blooms occur and provide fresh food to under-ice grazers or during ice melt to the pelagic and benthic biota.

Future changes: Ice formation will be much later (due to increased heat content of water) and ice melt slightly earlier compared to today. Entire Arctic will be ice free in summer likely by 2050. I expect that an ice algal bloom of similar magnitude as today will still occur and will be terminated by the ice melt. However the question is whether the changes from multi-year sea ice to seasonal sea ice will impact the ice endemic fauna of amphipods and nematodes leading to less favorable conditions for high Arctic birds, fish, and seals during periods of ice cover. Loss of sea ice might lead to increased upwelling along slopes, more mixing, more sediment input (less light for algae) etc.

Phytoplankton:

Phytoplankton contributes the majority of the annual primary production in any Arctic sea. After surviving several months without light, typically a single bloom occurs immediately following the ice melt with very high algal standing stocks. Often blooms occur at the pycnocline at depth of 20-50m which might be a challenge for remote sensing. Nearly

2000 algal species are known from the Arctic. The dense blooms provide excellent food quality and quantity for micro- and mesozooplankton and also provides distinct seasonal inputs into benthic systems. Depending on region the partitioning between pelagic and benthic fate varies.

Change: Changes in the ice melt regime will change the phenology of phytoplankton blooms with potential for increasing mis-match to needs by zooplankton and benthos. Changes in species composition (already observed with increase in smaller taxa in central Arctic) might additionally stress zooplankton populations and reduce input to benthos. Understanding partitioning between pelagic and benthic consumers is critical.

Zooplankton:

Several hundred zooplankton species are known from the Arctic including endemic copepod taxa. Arctic copepods and euphausiids are critical food for Arctic whales and seals as they are big and high in lipds. Different species occur in different parts of the Arctic. Fecal pellets are sinking at fast rates to the sea floor. Survival strategies over winter may include diapause at great depths or winter feeding on heterotrophs or sea ice algae. The role of small size classes of pelagic heterotrophs (bacteria, flagellates) is largely unexplored for many regions of the Arctic. However, wherever studied, those small size classes contribute significantly (at times over 50% to total biomass and to carbon flow) in the ecosystem.

Changes: Changes in water temperature will impact respiration, energy balance and also food availability. Similar to phytoplankton, more southerly species will have competitive advantage at increased temperatures. The role of microzooplankton as grazers and as food for mesozooplankton and e.g. fish larvae is largely unexplored and changes cannot be easily predicted. Role of winter survival, diapause, feeding in winter largely understudied due to logistical difficulties.

Freshwater:

The enormous freshwater input makes the central Arctic Ocean permanently stratified. It also causes estuarine patterns on the shelves (e.g. Laptev Sea) or close to river mouths with species complexes shifting from freshwater to brackish to salt water communities. Within the estuaries productivity and diversity is often reduced compared to full marine conditions.

The predicted increase in freshwater run-off will have great impacts on the epipelagic processes and needs to be addresses on a regional scale.

Recently surface water salinities in the Beaufort Seas have drastically decreased with unknown biological implications (e.g. osmotic stress on marine taxa, shift in species compositions etc).

In-flow of water into Arctic

Within the Bering Sea and Fram Strait, substantial inflow of Pacific and Atlantic water occurs either crossing the Arctic or being recirculated to the Atlantic. Advected sub-Arctic species and associated nutrient loads impact productivity and diversity patterns. For example, the very high nutrient Anadyr water (caused by upwelling along Bering Sea slope) sustains very high productivity values in the Chukchi Sea.

I am not aware how these inflow rates will change, however such changes do have the potential to substantially impact the high Arctic systems.

Suggestions:

The biggest gap in knowledge regarding the current system is region (many parts of the Arctic not studied, specifically the basins) and certain size classes (mainly viruses, bacteria, flagellates, rotifers, microzooplankton) or taxonomic groups (e.g. jellyfish). This will cause large uncertainties in the development of adequate models, but efforts in Europe (e.g. Slagstad group) and the US (Gibson at UAF) are underway to compensate for this.

Most urgently I would suggest to study the multiyear sea ice biological processes before it completely disappears from Earth within the next 40 years. I suggest experimental studies to evaluate rate changes (e.g. respiration,…) related to temperature and salinity of Arctic pelagic and benthic communities. Such equations are needed to develop adequate models. Furthermore mesocosm competition experiments between sub-Arctic and Arctic communities would allow to evaluate future potential community compositions including multiple environmental stressors. This will help to include the correct groups in future model structures. And as last point, we need more winter information from all Arctic Seas.

Benthos in the Pacific Arctic Region (PAR)

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Current condition of benthos in the PAR including vertical and horizontal connectivity

The Pacific Arctic shelf benthos in the northern Bering, Chukchi and Beaufort Seas is strongly influenced by the characteristics of mostly northward flowing waters originating in the Bering Sea. The nutrient-rich Anadyr water is upwelled onto the northern Bering Sea shelf and is then mixed with Bering shelf water and advected northwards onto the broad and shallow Chukchi Sea (see white paper on physical drivers). The Pacific winter and summer waters transit northward in both the western and eastern sectors of the Chukchi Sea (Weingartner et al. 2005). Only close to the northern Chukchi Sea outer shelf and slope do water masses of Arctic and Atlantic origin influence the region. The food supply resulting from these advected water masses and *in situ* production drive the distribution of benthic biomass and differences in food web structure between water masses (Grebmeier et al. 2006a, Iken et al. 2010, Grebmeier 2012). Taxonomic composition is not only structured by food supply and quality, but also by sediment grain size, hydrographic conditions such as bottom temperature and salinity, and ice scouring in shallow waters (Conlan and Kvitek 2005, Grebmeier 2012). Soft bottom sediments prevail in the PAR with the exception of small areas of boulder accumulations in coastal areas, and coarse sediments in Barrow Canyon and other areas of high current such as Bering Strait.

Nutrient-rich conditions of the Bering-Anadyr water result in regions of very high infaunal biomass (hotspots) concentrated in the St. Lawrence Island Polynya region, the Chirikov Basin, the southwest Hope Basin, and the northeastern Chukchi Sea (Grebmeier et al. 2006a, Grebmeier 2012). By comparison, the longer persistence of sea ice and associated impacts on production results in lower benthic biomass in the underlying sediments in the northwestern Chukchi Sea (Grebmeier et al. 2006a). Infaunal assemblages in the PAR are primarily dominated, in varying proportions, by amphipod crustaceans, polychaete worms and clams (Grebmeier et al. 2006a, Bluhm and Grebmeier 2011) with peak values of 25-60 g C m^{-2} in the listed hotspot areas. **These infaunal community biomass hotspots do not necessarily overlap with epibenthic hotspots as the latter are mostly driven by substrate characteristics and include many mobile taxa** (Bluhm et al. 2009). Regions of hard substrates increase the abundance of sessile epibenthic filter feeders such as sponges, bryozoans and ascideans. Otherwise, epibenthic communities in the PAR are mostly dominated, again in varying proportions, by echinoderms, especially brittle stars and sea stars, and by arthropods, in particular brachyuran crabs and also shrimp and hermit crabs, and by sea urchins, sea cucumbers, and gastropods (Frost and Lowry 1983, Feder et al. 2005, Bluhm et al. 2009). These epifaunal organisms contribute an estimated 25% (and up to 40%) to total benthic remineralization rates in the Chukchi and Beaufort Seas (Ambrose et al. 2001, Renaud et al. 2007). Epifaunal invertebrate biomass overwhelms that of demersal fishes in trawl hauls (>90% invertebrates), a clear difference to the Atlantic Arctic Barents Sea located at similar latitudes (Hunt et al. 2013).

On the narrow US Beaufort Sea shelf, benthic communities are strongly influenced by freshwater inflow from the Mackenzie River and smaller Alaskan rivers that carry terrestrial, mostly recalcitrant carbon, large sediment loads, and inorganic nutrients within them. These conditions result in **generally lower infaunal biomass (<10 g m^{-2})** than in productive areas of the Chukchi Sea, along with the deposition of terrigenous carbon into the nearshore food webs (Dunton et al. 2012). Curiously, however, snow crabs and some fishes are larger on the Beaufort Sea slope than on the Chukchi and Beaufort shelves (Logerwell et al. 2011, B. Norcross and L. Edenfieldt, Unv. of Alaska Fairbanks, pers. com.), and epifaunal biomass is higher on the upper Beaufort Sea slope near Barrow Canyon than on the Beaufort Sea shelf (A. Ravelo and B. Konar, Univ. of Alaska Fairbanks, pers. com.). This phenomenon can perhaps be explained by a combination of upwelling events of nutrient-rich comparatively warm Atlantic water onto the shelf (Pickart et al. 2009) and nutrient-rich outflow from Barrow Canyon at depth that gets deflected to the east (Mathis et al. 2007). In the deep Canada Basin, benthic biomass is drastically lower than on the adjacent shelves, presumably as a consequence of decreasing food supply (Bluhm et al. 2005, MacDonald et al. 2010).

The described large-scale patterns in benthic assemblage structure for both the Chukchi and Beaufort regions appear to have generally persisted over the last 4-5 decades of research where such long-term information is available. Local declines in infaunal biomass, however, have been documented in the northern Bering Sea south of St. Lawrence Island (Grebmeier et al. 2006b) and for infaunal amphipods in the Chirikov Basin (Coyle et al. 2007). These declines have consequences for spectacled eider duck feeding (Lovvorn et al. 2009) and gray whale distribution (Moore et al. 2003) because these species have preferences for particular kinds of clams and amphipods, respectively. The declines have been attributed to shifts in sediment grain size related to current speed, with largely unknown depletion effects from top predators. Time series of epifaunal organisms are sparse but where existent they show no indication of decline, but rather the opposite trend, if any (Hamazaki et al. 2005, Bluhm et al. 2009).

The biodiversity of the PAR benthos and the entire Arctic is not as depauperate as previously thought (compared, for example, to the Antarctic), and ranks 'moderate' on a global scale (Piepenburg 2005). Recent taxonomic inventories of the Chukchi and Beaufort Seas documented the occurrence of at least 1500 species of eukaryote fauna in the Chukchi Sea, and over 1000 species each in the less well inventoried US Beaufort Sea and central basin (Carey 1977, Gradinger et al. 2010) with >90% being benthic. Species accumulation curves suggest that inventories are not yet complete for these and other Arctic seas (Piepenburg et al. 2011, Bluhm et al. 2011a). While several new species have recently been described from the Chukchi Sea, new discoveries are most common on the less-well studied regions along the lower continental slope and in the adjacent Canada Basin (Bluhm et al. 2011b).

Why is this theme important to understanding the ecosystem and what knowledge gaps remain

On a global scale, Arctic shelves have comparatively high benthic standing stocks (Wei et al. 2010). The reason for this high biomass is that a higher proportion of pelagic production sinks to the seafloor in the Arctic than at low and mid-latitudes (Petersen and Curtis 1980). This **strong pelagic-benthic coupling** results in part from sea ice primary production, which occurs too early in the year to be utilized by undeveloped zooplankton communities and sinks largely ungrazed to the seafloor. Benthic ecosystems, therefore, integrate water column processes, and areas of high benthic (especially infaunal) biomass indicate persistently high carbon deposition. In the Arctic, this vertical integration happens over longer time periods (months to years) than in lower latitudes because of the slow growth and high longevity of many polar benthic organisms (Bluhm et al. 1998). Benthic biomass distribution patterns (in particular those of the mostly sessile infauna) can, therefore, be used as time-integrated indicators of long-term change (Grebmeier 2012). The changes in sea ice timing and characteristics as well as the warming and freshening Pacific water inflow (Woodgate et al. 2012) will have complex and largely unknown effects on sea ice and phytoplankton production and the timing and development of zooplankton communities, and consequently on the strength of pelagic-benthic coupling.

The benthic realm is also important to understand for its ecological function in supporting important prey, not only for benthic invertebrates themselves and for demersal fishes, but for bottom-feeding birds such as the threatened spectacled eider (Lovvorn et al. 2009) and marine mammals (Moore and Huntington 2008, also white paper on upper trophics). The latter include the bearded seal and Pacific walrus (Jay et al. 2012), both of which are subsistence harvested species, and the gray whale. Besides serving as prey, epifaunal communities include taxa of subsistence or commercial value farther south in Alaskan waters such as snow crabs, various species of shrimps, sea urchins, and sea cucumbers (Bluhm et al. 2009). Due to warming water, species range shifts can be anticipated in some of these and other species (Mueter and Litzow 2008), and monitoring taxonomic composition in addition to bulk abundance and biomass is necessary to detect future changes (Grebmeier et al. 2010).

Time series are necessary to evaluate the impacts of climate change and other ongoing human activities in the PAR (see white paper on anthropogenic stressors). The recent establishment of the Distributed Biological Observatory (DBO) in the northern Bering and Chukchi Seas (Grebmeier et al. 2010) is a promising effort to approach this issue. The DBO is an array of "hotspot" transects within the Bering and Chukchi Seas that are repeatedly sampled for biophysical parameters (hydrography, plankton, benthos, higher trophics) by a network of national and international partners to create long-term datasets along defined sensitive regions of the PAR (see white paper on hot spots). Additional monitoring locations in the Beaufort Sea and in the Canada Basin would be valuable as temporal coverage of benthic community biomass and structure over the past half century (i.e., the phase of most intense study in the PAR) is by far less complete in the Beaufort Sea than in the Chukchi Sea. Besides the need to monitor spatial and temporal patterns of benthic communities, **physiological consequences of changing climate conditions are poorly studied**. Our knowledge on species-specific temperature tolerance ranges is as scarce as that on the physiological capacity of benthic organisms to acclimate or adapt to warming or otherwise changing conditions, although research on model species has greatly advanced our general understanding on the topic (Pörtner 2010).

While standing stocks are relatively well-documented across much of the PAR (with the exception of the contribution of benthic meiofauna), **little is known about the rates of secondary production that maintain the locally high benthic biomass**. Studies on population dynamics including age, growth and reproductive rate estimates are needed to estimate secondary production. Similarly, little is known about the **magnitude of annual benthic biomass removal by higher trophic level organisms or the dynamics of larval supply and dispersal** that form the basis for replenishment of benthic biomass. Accordingly, dynamic predictive models including growth rate measurements will be essential to gain an understanding of future changes in Arctic shelf benthos.

Parts of the PAR receive large amounts of river inflow that transports terrestrial carbon into the marine system (Raymond et al. 2007). While terrestrial carbon was long thought to be of little nutritional value for marine organisms, recent studies have begun to document that this terrigenous carbon can get assimilated into marine nearshore and shelf food webs (Dunton et al. 2006, 2012, Iken et al. 2010). More work is needed to **clarify the role of terrestrial organic material for food webs across the shelf and slope areas** during a time of increased river run-off (McClelland et al. 2006).

How will benthos in the PAR change over the next 3-4 decades

In the advective area of Bering Strait, northward transport carries pelagic larvae of benthic organisms into the Pacific Arctic. Here, **predicted increasing temperatures (IPCC 2007) and observed increased volume transport through Bering Strait (Woodgate et al. 2012) are expected to bring in more boreal and sub-Arctic species** than in the past, perhaps resulting in intermittently increased biodiversity and increased levels of competitive interactions between local taxa and new arrivals (Weslawski et al. 2011). In addition to these distribution range changes of benthic organisms, for which examples have already been documented in the PAR, **metabolic rates can be expected to increase, resulting in increased demand for food**. This increased carbon demand could potentially be met by the observed and predicted increase in pelagic primary production that results from extended open water periods (Arrigo et al. 2011) or by rich under-ice blooms (Arrigo et al. 2012). Other predictions, however, **project shifts in carbon flux** in the extended areas of increasingly earlier sea ice retreat resulting in pelagic-dominated systems rather than the currently benthic-dominated systems (Carroll and Carroll 2003). Time series studies may be able to document if, when and to what extent such shifts will occur. For the foreseeable future, sea ice formation in the PAR in the winter will probably still allow the development of ice-related spring blooms in cold water that facilitate export production to the benthos before substantial pelagic grazing occurs. Higher spatial resolution of IPCC scenarios for the ocean on regional scales and inclusion of more relevant variables for seafloor communities (such as vertical flux rates and sediment characteristics) would improve our ability to model the future PAR benthos and its linkages to other components of the food web over short and long time periods. Where and when shifts in carbon flow and resulting benthic biomass and community structure occur, they are expected to affect the distribution and abundance patterns of marine mammals (Moore and Huntington 2008). To date, relatively few studies have clearly documented biological consequences of climate change in Arctic benthic systems (Wassmann et al. 2010) and this gap should be filled in the coming decade.

Key references for further reading (pdf files attached)

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Fishes of the Chukchi and Beaufort Seas

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Baseline information about marine fishes in offshore ecosystems in the northeastern Chukchi and Beaufort Seas is sparse (Johnson, 1997; Power, 1997; Mecklenburg et al., 2008). Baseline data cannot be reconstructed using historical commercial fisheries harvest data because there are no commercial fisheries in federal waters of the Alaskan Arctic (Zeller et al., 2011). The Chukchi and Beaufort Seas are north of the regular fish-trawl research surveys conducted by NOAA Fisheries. Fishes are much less abundant than invertebrates in research bottom tows (Rand and Logerwell, 2010; Bluhm, et al., in prep). The only knowledge of offshore demersal fish communities in the Chukchi Sea comes from scientific cruises in the eastern Chukchi Sea from 1959 to 2012. From 1973 through 2008, 16 research cruises collected 59 species of fishes from 17 families in the northeast Chukchi Sea at some stations north of 70^{o} N (Norcross et al., 2013). Over time Arctic cod (*Boreogadus saida*) was the most abundant demersal (Alverson and Wilimovsky, 1966; Frost and Lowry, 1983; Barber et al., 1997) and pelagic (Eisner et al., 2012) species. The same fish families dominated the northeast Chukchi throughout the historical collections (Norcross et al., 2013): cods (Gadidae), sculpins (Cottidae), eelpouts (Zoarcidae), and righteye flounders (Pleuronectidae). In the 1990s and 2000s, the dominant fishes caught were: Arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*), Arctic staghorn sculpin (*Gymnocanthus tricuspis*), shorthorn sculpin (*Myoxocephalus scorpius*), eelpouts (*Lycodes* spp.), Bering flounder (*Hippoglossoides robustus*). Diversity was higher in 2004–2008 than in the preceding decades, but that is muddled by net mesh differences (Norcross et al., 2013). Information about fish in offshore waters >20 m in the Beaufort Sea is even more meager than for the Chukchi Sea. Only 34 species of demersal fishes were captured in 1976 – 1977 (Frost and Lowry, 1983) and in 2008 (Rand and Logerwell, 2010). The dominant fish taxa in 2008 in the Beaufort Sea (Logerwell et al., 2011) were cods – Arctic cod, walleye pollock (The*ragra chalcogramma*); sculpins – warty sculpin (*M. verrucosus*), ribbed sculpin (*Triglops pingelii*), bigeye sculpin (*T. nybelini*), and eelpouts – marbled eelpout (*Lycodes raridens*), Canadian eelpout (*L. polaris*). While the same families dominated both seas, the apparent differences in abundance may be due to specific collection locations and not simply to differences between Chukchi and Beaufort Seas.

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Seabirds

Alan Springer

Current condition

Seabirds are by far the most abundant and diverse of the upper trophic level taxa in the northern Bering, Chukchi, and Beaufort Seas (BCB), with millions of individuals of 34 species nesting in the US EEZ and millions more of six species migrating to it in summer. They owe their spectacular abundance primarily to the advection of nutrient and biologically rich water in the Anadyr Current that originates off the continental shelf of the Bering Sea and flows north through Bering Strait into the Arctic Ocean. Mesoscale production processes in key locations such as Ledyard Bay and Kasegaluk Lagoon further enhance the quality of the environment for seabirds.

Among the most abundant and/or conspicuous of the breeding seabirds, auklets, murres, kittiwakes, and guillemots represent zooplanktivore, omnivore, and piscivore foraging guilds. They directly sample, by preying upon, many of the principal zooplankton and fishes responsible for the majority of carbon and energy flow through pelagic food webs in the BCB. These include large calanoid copepods, euphausiids, and Arctic cod. They also sample sand lance, a key prey of several species of seabirds, that are supported by the more abundant smaller taxa of copepods and meroplankton.

Auklets – Bering Strait

Least and crested auklets are planktivores—least auklets specialize on large calanoid copepods, particularly *Neocalanus* and *Calanus*, and crested auklets specialize on euphausiids but consume at times important amounts of *Neocalanus* as well. Studies of auklets on St. Lawrence I. in 1981 provided the first unequivocal evidence of the importance of the Anadyr Current in maintaining the flourishing productivity of the Bering Strait region—that it advected northward an immense amount of large oceanic zooplankton from the same basin source as the macronutrients that were recognized in the mid-1980s as being responsible for the prolific regional primary production. Previous (1960s) and subsequent (2000s) work with nesting auklets demonstrated the sensitivity of the birds to variability in the availability of prey, which is likely affected by annual production and entrainment far to the south, the predator field along the route from the basin to the strait, and atmospheric pressure and wind fields that alter volume transport of the Anadyr Current and mesoscale current patterns near the island.

Murres and kittiwakes – Chukchi Sea

Increases of ~300% in numbers of nesting murres and kittiwakes at Cape Lisburne overall since the mid 1970s, and primarily since the late 1980s for murres and the late 1990s for kittiwakes, correspond to pronounced shifts in mean climate state over the North Pacific in about 1989 and 1998. The growth of the kittiwake population aligns well with a rising trend in advective heat flux into the Chukchi from the Bering in the 2000s. Water temperature, via linked functional relationships, influences the timing of annual sea ice retreat, the timing and magnitude of primary production, the rate of seasonal ocean warming and the effect that has on the timing and magnitude of secondary production and the abundance of sand lance that are crucial to high reproductive success of the birds. Thus, water temperature apparently drives an ecological phenology on the eastern Chukchi shelf that influences in large measure pelagic food web productivity from phytoplankton to seabirds.

Black guillemots – Beaufort Sea

Guillemots are endemic to the Arctic Ocean, nesting in the northern Chukchi and Beaufort seas and wintering within the pack ice of the BCB. They depend upon a single species, Arctic cod, for the bulk of their annual energy requirements. Long term studies of guillemot foraging strategies, diet, productivity, demography, and abundance at Cooper Island have documented their role as sentinels of ecosystem change that accompanies the ongoing loss of sea ice.

Why seabirds are important

Seabirds are sensitive indicators of variability in key Arctic forage species and pelagic food webs across a diversity of ecoregions in the BCB from oceanic advective, to shallow shelf, to cryopelagic. Moreover, they are tractable—they are highly visible, easily accessible, and abundant. Comparatively long and detailed time series of diets, productivity, and numbers provide a rich background and strong foundation for assessing future changes in Arctic marine ecology.

Key knowledge gaps

- What is the source and magnitude of variability in volume transport of the Anadyr Current and in the inventory of nutrients and biota it carries with it?
- What are the constraints on new primary production (NPP) and incorporation into pelagic food webs?
- How will growing numbers of whales in the BCB alter pathways and rates of carbon flow through pelagic food webs?

The future

Shifts in decadal scale climate states are predicted to continue to occur, but the physical and biological characteristics of future states cannot be predicted at this time. The ongoing secular increase in global temperatures may lead to ice-free summers in the Arctic, and overall there will be winners and losers. For example, we would predict that Arctic cod and their predators would be losers, while boreal sand lance and their predators could be winners. But there will continue to be winter ice formation across the BCB, and in many contexts the magnitude of summer sea ice recession will not be more important than changes in the rate and timing of retreat in spring-summer and the effect that has on food web production budgets due to alterations in phytoplankton production and community structure, trophodynamic phasing from this base upwards, and the thermal environment. There is no indication that seabirds in general in the BCB will experience remarkable changes in status. The principle exception is the black guillemot, which may decline appreciably because of nutritional stress.

Despite lengthening growing seasons due to longer ice-free summers and thus more sunlight, it is unlikely that the recent trends in rising primary production will continue for long across much of the BCB shelf—nutrient availability will ultimately constrain NPP to, probably, moderate levels characteristic of the shallow inner and middle domains of the Bering Sea. In the future, as now, much, perhaps most, of NPP will be weakly coupled to pelagic food webs, fueling primarily benthic systems of importance to some sea ducks and marine mammals. This is not to say however that pelagic systems have not benefitted from the recent rise in NPP, as post bloom production can be captured by larger herbivorous zooplankton such as *Calanus* and euphausiids that are important conduits for carbon and energy flow to many fishes, seabirds, and cetaceans.

Changes in physical forcing and biological response far to the south along the outer continental shelf and shelf edge in the Bering Sea also might be important to ecosystem dynamics on the BCB. The inferred stability of physical properties of the Anadyr water mass in this century and the implications must be further evaluated before predicting future conditions.

Growing numbers of cetaceans, particularly bowhead, humpback, and fin whales—representing a return to the "old normal" as animals reoccupy historic foraging grounds in the BCB—will alter abundances of large zooplankton and schooling forage fishes that are important prey resources for many seabirds and other upper trophic level predators. The recovery of large whales following dramatic reductions during whaling eras in the 19th and 20th centuries is happening at the same time as rapid climate change in the western Arctic. In a similar way, a northward range expansion of killer whales, as already seen in the eastern Canadian Arctic, would shift apex predator dominance away from polar bears and further alter pelagic and benthic food webs. Disentangling bottom up effects mediated by climate change from top down effects mediated by whales on ecosystem structure and function across the BCB will be a challenge in the coming decades.

Biological Hotspots in the Pacific Arctic: Physical drivers, ecosystem productivity and sensitivity to climate change

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1. Introduction: Current Condition of Hotspots and System Connectivity

"**Benthic Biomass Hotspots**" occur on the continental shelf in the northern Bering Sea between St. Lawrence Island and Bering Strait, in the southern Chukchi Sea, and in the northeast portion of the Chukchi Sea, including upper Barrow Canyon (Figure 1; further citations in Grebmeier 2012; also see Bluhm et al. benthic white paper). **We define these localized biological features as annually-persistent and seasonally-consistent regions of high water column and benthic biomass.** By comparison, biomass of both primary producers and benthic macroinfauna are diminished on the narrow continental shelf of the Beaufort Sea (Dunton et al. 2005), but these hotspot features are again present in the Cape Bathurst Polynya area of the Canadian Arctic Archipelago (Conlan et al. 2008). In the Beaufort Sea, both enhanced production (primary and secondary) occur along the outer continental slope (Logerwell et al. 2011, see Pickart et al. white paper), although they are not as well defined as the benthic hotspots on the broad continental shelves of the northern Bering and Chukchi seas. All of the continental shelf "hotspots" are directly tied to hydrographic processes that bring high nutrients onto the shelf and support high algal production, often where a reduction of current speeds facilitate higher export production of particulate carbon to the benthos (Grebmeier et al. 2006a). In addition, cold, early season Pacific winter water temperatures limit zooplankton growth, thus minimizing the impact of the overall grazing capacity of zooplankton and resulting in high biomass benthic infaunal communities at the hotspot sites (Grebmeier et al. 2006a, 2009). For details of the physical dynamics and benthic populations of the northern Bering, Chukchi and Beaufort shelf and slope systems, please see the Pickart et al. and Bluhm et al. white papers, respectively.

Satellite and field observations indicate the annual reoccurrence of high chlorophyll features at the benthic hotspot sites (Hill and Cota 2005, Lee et al. 2007), **whereas annual shipboard sampling provides evidence of continued persistence of underlying non-motile, macroinfaunal organisms that benefit from the high carbon export to the underlying benthos at these sites** (Grebmeier et al. 2006a,b, Grebmeier 2012). The benthic biomass hotspot sites support benthic feeding marine mammals, such as gray whales, walrus, and bearded seals (Moore et al. 2003, Jay et al. 2012, Moore et al. accepted), and in certain areas, diving seaducks (Lovvorn et al. 2009). **By comparison, zooplankton hotspots are somewhat more ephemeral, but do indicate repeatable patterns of organic carbon transport.** For example, those sites allowing seasonal build up of water column biomass, such as the late spring-summer accumulations observed in the southern Chukchi Sea (Bluhm et al. 2007), water mass frontal zones, and via wind- and current-induced concentrating mechanisms (e.g. upwelling) at the slope and canyons (e.g., Barrow Canyon) and nearby shelf areas provide indicators of water-column or epibenthos biomass hotspots (Ashjian et al. 2010, Walkusz et al. 2012). Although we focus on benthic biomass hotspots in this white paper, we also recognize there are key locations for concentration of zooplankton used by pelagic-feeding, upper trophic species, including bowhead whales (feeding on copepods and euphausiids), belugas (feeding on forage fish, including arctic cod), and pelagic seabirds (feeding on copepods, small fish, and gelatinous zooplankton).

2. Why is the theme important to understand the ecosystem and what knowledge gaps remain?

Benthic infauna that remain in place in the sediments as adults respond to variable levels of export production, building up biomass over multiple years-to-decades and maintaining persistent community patches or "hotspots" that provide important prey to mobile epibenthic animals and upper trophic level animals, particularly marine mammals and diving seabirds. In addition, persistent advective sites, such as Barrow Canyon that is located at the interface of Pacific-produced Bering Sea waters (winter and summer types) and upwelled Atlantic water, are important sites for pelagic-feeding upper trophic levels, including bowhead whales and seabirds (Moore et al. accepted). **Understanding biological**

hotspots is important in evaluating the overall system as these sites track the status and change in physical forcing, sea ice retreat, and ecosystem response in a shallow water continental shelf system that is being stressed by both climate change and anthropogenic impacts (e.g., oil development, transportation) (see Wassmann et al. 2011).

There are numerous knowledge gaps with respect to the mechanisms driving the development and persistence of benthic and pelagic biomass hotspots. We have had few growth rate measurements of benthic macrofauna or zooplankton, but **rate measurements are critical for determining population dynamics and to build scenarios to test change** (e.g., changing temperature effects). With regard to pelagic hotspots, the seasonal dynamics of upwelling, advection and eddy formation require additional focus, as they are the primary physical drivers of prey-delivery. Time series measurements, with simultaneous biological, biogeochemical and physical measurements undertaken in a coordinated fashion are needed, such as the developing Distributed Biological Observatory (DBO) for the Pacific Arctic region (Grebmeier et al. 2010, 2012). However, **we still lack spatial and temporal coverage at a systems-level to monitor hotspot dynamics and thus we cannot evaluate entirely the key forcing factors at the appropriate scales.** Ultimate goals are to develop nested models that incorporate a full suite of benthic biogeochemical and metabolic measurements that can ultimately be mounted using a DBO sampling approach. Another area of needed study includes observations of the small faunal size fractions (e.g., meiofauna, microzooplankton, microbes) that can respond quickly to climate change forcing. This is critical for tracking and evaluating hotspots as windows to the health of the Pacific Arctic ecosystem. Tracking prey-predator interactions, and using the upper trophic levels as sentinels of important hotspot feeding sites, will also help determine the processes that facilitate persistence of prey biomass at specific locations on an interannual basis.

3. How will hotspots change in the Pacific Arctic region over the next 3-4 decades?

We can only speculate about future change, based on the limited time series of measurements (that are the basis for the developing DBO) collected at benthic hotspots in the northern Bering and Chukchi seas. The DBO concept relies on coordinated, international sampling by a network of ships at these specific high productivity locations, which are sampled on a repeated basis as research vessels transit the Pacific sector of the Arctic. Note that 1-2 DBO lines are currently being considered for the Beaufort Sea, particularly at the outer shelf/upper slope regions and near Cape Bathurst in the eastern Beaufort Sea (2013 DBO data report, in prep.). Based upon projections of continued sea ice retreat, it is reasonable to assume more wind forcing on open waters, greater fetch, and more mixing that can increase sediment resuspension over the shallow shelf systems. Continued seawater warming and freshening with increased riverine inflow would influence levels of primary production (depending on nutrient loading and stratification) across these regions. Even with transport through Bering Strait increasing, warming, and freshening (Woodgate et al. 2012), **we anticipate high regional productivity will continue at the areas of highest nutrient loading** in the northern Bering Sea, SE Chukchi Sea and Barrow Canyon. The **projection of enhanced upwelling in Barrow Canyon** may expand the footprints of the NE Chukchi Sea and Barrow Canyon benthic hotspots, depending on the timing of zooplankton grazing and life cycles. However, even with more upwelling along the outer Chukchi and Beaufort seas (see Pickart et al. white paper), it is less likely that benthic hotspots will develop on the slope owing to the general pattern of reduced benthic biomass with depth in the region (Bluhm et al. 2012). Nevertheless, some increased patches of benthic populations, such as mobile epibenthic animals and demersal fish, could persist as new extensions of these high productivity zones (see Bluhm et al. benthos white paper).

Changes in wind-induced upwelling of nutrients will likely enhance productivity both at the slope and in Barrow Canyon, thus increasing annual primary production as well as the presence of zooplankton biomass and grazing pressure, but again dependent upon seawater temperatures and growth rates at the appropriate times of the year. **However, the system is still expected to reset thermally every year for the foreseeable future via ice formation in the winter,** so the Polar mixed layer will be near or below freezing from winter to spring, thus inhibiting Pacific zooplankton from overwintering and interfering with early grazing in the spring. This process should continue the pattern of a time lag between the initiation of primary production and secondary production and consumption, with continued high direct export to the benthos. The benthos is sustained despite boom and bust (or feast and famine) cycles in water column production, and are furthermore adapted to near freezing temperatures, so it is also possible that large system changes at the northern hotspots may not be apparent to any great extent. The same scenario probably will not hold for the northern Bering Sea/southern Chukchi Sea hotspot complex that is experiencing longer periods of warmer seawater (both at the surface and at depth) and is already experiencing declines and northward spatial shifts in biomass hotspot locations (see http://www.arctic.noaa.gov/dbo/related_ts.html for examples tied to DBO time series data).

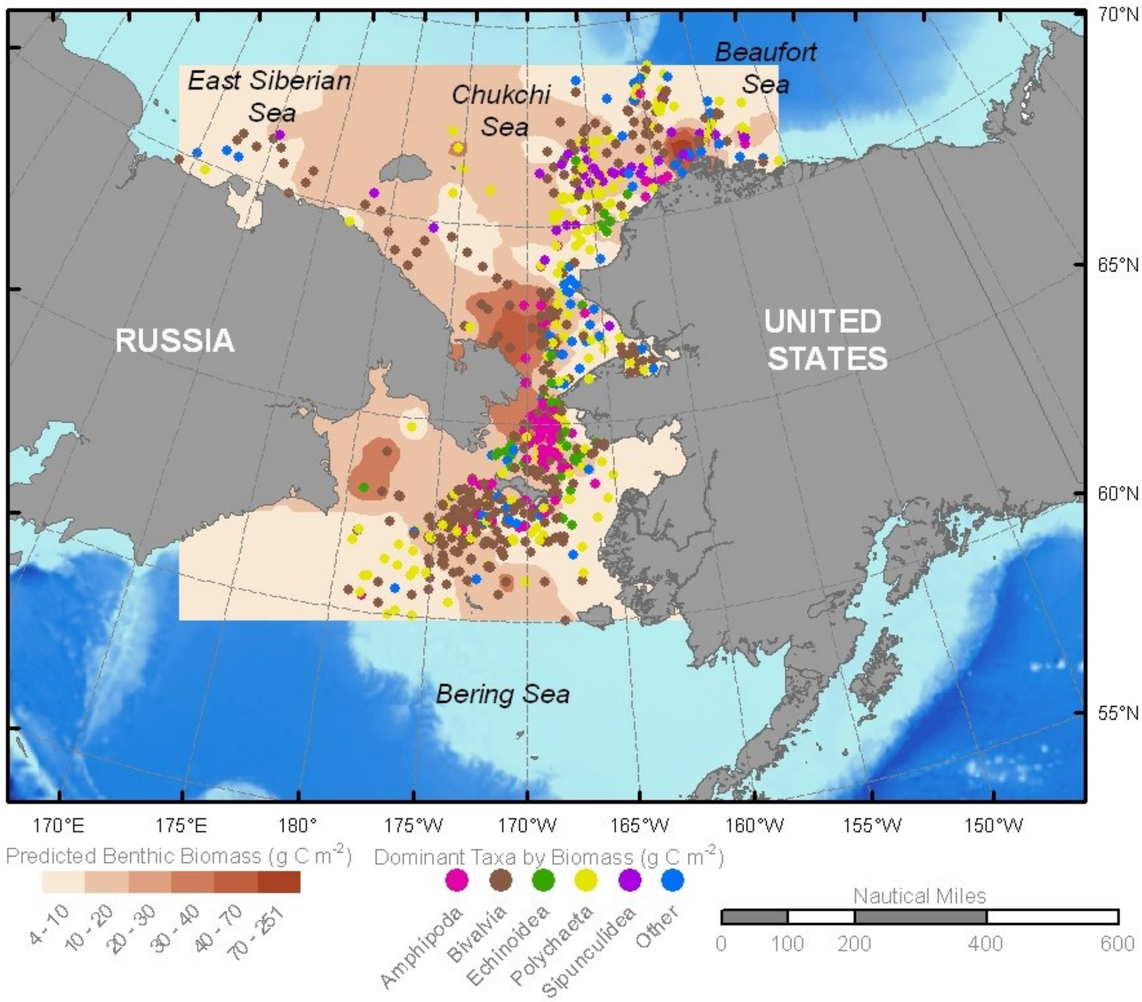

FIG 1. Macroinfaunal benthic hotspots by biomass, along with dominant infaunal type, in the Pacific Arctic region (data updated and modified from Grebmeier 2012).

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Five key references (pdfs as separate attachments)

Grebmeier et al. 2006a, 2009, 2010, 2012; Grebmeier 2012; also upper trophic graphics pdf (Sue Moore)

The Impact of Anthropogenic Activities in the Changing Arctic Ocean

Robert Spies[1], PhD, and Stanley Senner[2], MS

The northern Bering, Chukchi and Beaufort seas ecosystem is still wild and substantially pristine in comparison to other seas. This is true even though the Arctic coast has been occupied by indigenous people for millennia and has experienced significant anthropogenic influences, such as whaling operations starting in the 17th century. However, discovery of oil at Prudhoe Bay in 1968 had a transforming effect on the landscape of the central Arctic, and many other changes are now evident or anticipated in the marine environment. Development of a conceptual ecosystem model for the Arctic marine ecosystem is especially timely as the pace of change accelerates and important policy and regulatory decisions are pending. In this context, we discuss six types of significant anthropogenic influences. The need to detect their effects should inform development of the conceptual model, which in turn should serve as a foundation for retrospective syntheses of Arctic marine science and for design and implementation of a comprehensive, integrated research and monitoring program.

Climate Change

The ecological implications of the rapid loss of summer and fall sea ice and warming temperatures are just beginning to become apparent, but are subjects of intense study. A recent literature review on range shifts, changes in abundance, growth, condition, behavior and community composition in the Arctic revealed 51 instances of climate change impacts (Wasserman et al., 2011). However, due to the lack of baseline data in many areas (e.g., the Siberian Shelf) and dearth of long time-series studies or extended monitoring, much remains to be done to understand the implications of such phenomena as shifts in the quantity, quality and timing of algal production from two sources: underneath sea ice and open water conditions (Boetius et al., 2013; Leu et al., 2011). Is overall marine production going to increase? Is there going to be a mismatch between the phenology of key Arctic marine species (e.g., planktonic copepods and fish) in relation to new annual production? As Arctic waters warm there will be a general shift of boreal species into the Arctic and long-term ecological changes will likely be extensive. Another area of intense interest is the shifting habitat of walrus, ice seals and whales, all which have close if not obligate relationships with sea ice and ice edges.

Acidification

High latitude oceans are more susceptible to acidification because of the greater solubility of CO_2, which reduces carbonate ion concentrations and leads to undersaturation of $CaCO_3$. Marine animals with aragonitic $CaCO_3$ in their skeletons are especially at risk initially, e.g., planktonic pteropods, crabs, and bivalves. At present, the surfaces of the Bering Sea and the Canadian Arctic Ocean in the summer are near or below saturation levels with respect to aragonite, and it is expected that the Arctic Ocean will be widely undersaturated by 2019 (Mathis et al., 2011; Yamamoto-Kawai et al., 2009). In addition to the ongoing increases in global CO_2 concentrations, this large recent shift toward undersaturation, at least in the Canadian Arctic, is also due to melting sea ice and contributions from increased upwelling as the ice edge melts back farther than the edge of the continental shelf in summer and fall and accelerates upwelling of deeper and less $CaCO_3$ saturated water. Increased phytoplankton production may to some extent

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ameliorate undersaturation, but specific outcomes of the various contributing processes, including potentially increased biological remineralization, are not known (Bates and Mathis, 2009). A conceptual model capturing the likely decreasing pH will need to account for the potential loss of organisms with aragonite skeletons and physiological processes depending on the current carbonate chemistry of sea water.

Noise Pollution

Sound is a primary information source that aids marine mammals in locating food, mates and ice-free surface water and in avoiding predators. The Arctic Ocean, with a few exceptions, is a relatively pristine environment with regard to anthropogenic noise that might interfere with reception and interpretation of such information, though there may be some effects of noise from existing facilities, e.g., displacement of migrating bowhead whales around the Northstar Platform complex in the Beaufort Sea (McDonald et al., 2012). Projected increases in vessel and air traffic and oil and gas activities are expected to rapidly increase anthropogenic noise levels in the Arctic Ocean and potentially result in displacement or interference with normal life history patterns of Arctic marine mammals. For example, walrus seem more susceptible to noise as their shrinking ice flow habitat forces more of them to haul out on land. More work is needed on the sensitivity of individual mammal species to anthropogenic sound, including thresholds and potential interference within the context of the often complex acoustic environment of the Arctic Ocean (Moore et al., 2012).

Oil and Gas Exploration, Production and Transportation

Oil and gas activity will have consequences for the Arctic Ocean, including noise and light pollution, contamination, disturbance, vessel strikes on marine mammals and alteration of coastal habitats. In the marine environment, however, the greatest concern is for a large oil spill from a well blowout, pipeline rupture or vessel accident (NRC, 1994), and there is every reason to believe that a major spill would be problematic with regard to cleanup and potential impacts on marine life. The likely consequences of such a spill are deaths of seabirds, some marine mammals and other pelagic organisms from floating slicks and suspended particulate and dissolved petroleum hydrocarbons. The rich benthic communities of the Chukchi Sea, which have developed to exploit suspended and sinking particulate food from under sea ice algae and phytoplankton, will be impacted by particles of oil in the water as oil in slicks breaks down and is dispersed during turbulent conditions. Since the impact of a spill varies with the amount of oil, weather and ocean conditions, season, and stochastic changes in wildlife distributions, modeling the physical behavior and ecological effects of a future spill impact has large potential errors.

Vessel Traffic

Vessel traffic in the Arctic Ocean is presently light, but increasing and may rapidly accelerate with oil and gas exploration and exploitation, increased tourism and the opening of valuable trans-Arctic shipping routes (Alaska Northern Waters Task Force, 2012). Potential impacts of increased vessel operations include: oil spills; discharge of sewage, garbage, metals and other contaminants by routine vessel operations; generation of low frequency noise from propellers and engines and high frequency sonar; discharge of ballast water containing contaminants and non-native species; strikes of marine mammals (e.g., bowhead whales, Citta et al., 2012); and discharge of gaseous and particulate airborne wastes, especially black carbon that reduces albedo and hastens melting of snow and ice (AMAP, 2011; Arctic Council, 2009).

Contaminants

Petroleum hydrocarbons from a major oil spill are an immediate local threat, but would impact Arctic animals already exposed to a variety of persistent organic pollutants that arrive in the atmosphere mainly from lower latitudes in a kind of Arctic haze. These atmospheric contaminants come out of the atmosphere because of the severe cold and get incorporated into the tissues of marine plankton at relatively low concentrations, but which in many cases are biomagnified in the Arctic food web and reach concentrations that potentially interfere with a number of hormone-mediated physiological processes, such as reproduction. Because of their position at the apex of the Arctic food web, polar bears may be at greatest risk of negative effects from bioaccumulated contaminants (Muir et al., 1999). Among the harmful contaminants are: methyl mercury, polybrominated diethylethers, organochlorines (chlordanes, hexachlorohexanes, PCBs and DDTs), and perfluoroalkyl compounds (Kelley et al., 2009; Muir et al., 1992).

Cumulative and Interactive Effects

Marine organisms do not necessarily lack some ability to adjust to a changing ecosystem, but anthropogenic influences do not act in isolation of natural temporal or spatial variability and there is great concern about cumulative or interactive effects involving combinations of natural or anthropogenic effects over time and space (at various scales) (e.g., Halpern et al. 2008). Contaminants, for example, may accumulate over time, while the simultaneous loss of sea ice and disturbance from aircraft may interact to exacerbate impacts on walrus. Although the federal government must assess cumulative impacts as part of NEPA compliance, there is no universally accepted approach for such analyses (Holland-Bartels and Pierce, 2011) and many analyses lack a strong scientific foundation. Cumulative effects analyses in the Arctic are also plagued by lack of data, especially in long time series (NRC 2003). Development of a conceptual model for the Arctic marine ecosystem should assist in structuring the analysis of cumulative effects and in designing a monitoring scheme that will provide the necessary data to support evaluation of cumulative effects and an adaptive approach to management and conservation in the Arctic.

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Development of a conceptual model of the Arctic Ocean ecosystem
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Together, the Bering, Chukchi and Beaufort Seas cover a vast and ecologically diverse area of the Pacific Arctic region. A comprehensive Pacific Arctic marine ecosystem model at its coarsest scale should consider atmospheric physics and chemistry, ocean and ice dynamics, terrestrial and coastal inputs, marine bio-geo chemistry, fish, fisheries and human interactions. Thus, development of a conceptual ecosystem model for these northern seas could include all ecosystem components from bacteria through to humans and the physical environment in which they are all contained. Due to the very different time and space scales on which the various ecosystem components act, a single model, while comprehensive, would be impractical at best and dysfunctional at worst. As with any modeling effort, development of a conceptual ecosystem model for the northern Bering, Chukchi and Beaufort seas needs to take into account the questions one hopes to address and then build a tool/suite of tools that comprise only the necessary constituents, interacting at appropriate time and space scales to adequately capture dynamics. This brief focuses primarily on the lower-trophic level components of a marine ecosystem model for the region of interest.

Essential components

Even when considering just the lower-trophic level component of an Arctic marine ecosystem model there are a number of choices to make concerning the number of biological/chemical components to include. It is not really possible to make such a selection without focused research questions in hand. However, the northern Bering and Chukchi seas are both very shallow so benthic-pelagic coupling is likely to be of primary importance. Therefore, in addition to the traditional components of a lower-trophic level marine ecosystem model (i.e. nutrients, phytoplankton, zooplankton) a model for this region should represent the important benthic processes so that variability in the partitioning between the benthic and pelagic ecosystems, and the resultant impact on the Arctic food web can be explored and understood. Even in the face of a summer sea-ice loss there will likely always be sea-ice during spring in theses northern seas. Sea-ice algae is known to be the primary source for primary production in the spring in the Chukchi Sea, and is likely of similar importance in the other regions. As such, an ecosystem model for this region needs to include an adequate representation of the ice-biology. Very few ecosystem models have been applied to the Chukchi and Beaufort seas at present. A comprehensive reference list for physical and ecosystem modeling efforts in the Pacific Arctic region can be found in Deal et al. (in press), which provides a summary of recent progress and future challenges in bio-geo-chemical modeling of this region. To date, the only lower trophic level model that I am aware of which includes representations of both ice-biology and the benthos is the BEST-NPZ model developed by Gibson et al for the Bering Sea ecosystem.

Importance of ecosystem modeling to understanding the ecosystem

Ecosystem modeling can be a powerful tool for synthesis of knowledge on an ecosystem and can highlight important missing information links. Historically the temporal and spatial resolution of Arctic ecosystem observations is relatively poor. Because of its remoteness and harsh environmental conditions, observational sampling in this region at space-time scales sufficient to elucidate the major factors affecting ecosystem dynamics is challenging, if not impossible. As ecosystem observations at any point in space and time are the result of complex physical and biological processes affecting the biological community, low spatial and temporal resolution can complicate interpretation of field data; it is often difficult to know just how representative a single observation on a given day really is. At best, a sampling program may be able to revisit a site in these northern seas once or twice in a given year. Extrapolation of this data, in an effort to understand and predict the finer spatial scale, seasonal, inter annual, and inter decadal dynamics would be impossible without the implementation of a quantitative ecosystem model. Because of the relative low cost associated with running models, it would be possible to develop a suite of ecosystem models that covered the Pacific Arctic region of interest with varying degrees of complexity and resolution (in time and space). Additionally, ecosystem models can really excel in the quantitative interpretation of knowledge of past ecosystem states to constrained predictions of future ecosystem states, and as test beds for 'what-if' scenarios, a particularly pertinent approach in understanding Arctic ecosystem dynamics since this region is changing at such a rapid and unprecedented rate.

Key knowledge gaps

An ecosystem model for the Bering, Chukchi and Beaufort Sea region will primarily be limited by available data of an appropriate resolution with which to validate. The 'observational' and 'modeling' component of an Arctic ecosystem program should be developed in tight collaboration to ensure that the data collected is suited for model validation efforts. Biomass of plankton and concentration of nutrients are necessary to constrain the model but should be collected in such a fashion that error-bounds can be put around observations. Equally important are the process orientated studies which relate rates i.e. phytoplankton growth rates, zooplankton grazing etc. to the state of the environment (temperature/light availability etc). These relationships form the core of the ecosystem model and enable the prediction of ecosystem behavior under alternative physical states.

All ecosystem models that have been applied to this the Pacific Arctic region at present track only a few phytoplankton and zooplankton components. With rapid ocean warming and sea ice loss, simulation of future ecosystem response in the Pacific Arctic will be hampered by unknowns including the introduction of 'new' species that are either newly advected to the region (foreign) or were always present in minority but able to survive and thrive under the new conditions. This could have a significant impact on the Arctic food web structure, including the higher trophic levels that constitute important coastal and marine resources. To capture these dynamics, a model would need to be constructed in such a way as to allow introduction and evolution of biological components over multiple decades. One approach that might prove fruitful could be the development of a lower trophic level model for the region that focused on emergent properties of marine ecosystems - essentially setting up a system that would allow multiple cell types to exists and establish themselves, given the appropriate environment (Allen and Polomene, 2011). While such an approach would have been computationally prohibitive only a few short years ago, today, due to the low cost of high performance cpu's, it seems quite attainable.

Resolution and coverage

It is not possible to consider the ecosystem dynamics of the northern Bering, Chukchi and Beaufort seas in isolation. The Bering Strait in the northern Bering Sea is an important gateway to the Arctic Ocean and variations in the flux of water, nutrients and biological constituents through this narrow strait could have significant impacts on ecosystem dynamics in both the Chukchi and Beaufort seas. However, ecosystem dynamics in the northern Bering Sea itself are deeply connected to dynamics in the rest of the Bering Sea. Dynamics in both the Chukchi and Beaufort seas are governed by advection and as these seas are openly connected to the Arctic Ocean proper they are influenced by physical oceanographic processes that occur on a broad scale. Accurate, high resolution modeling of physical ocean/ice properties would be essential to achieving successful modeling of the Bering, Chukchi and Beaufort Seas. For example, the Bering Strait is only 50km wide at its narrowest so a model of sufficiently fine resolution (~5km at a minimum) would be required to adequately resolve advective processes through the strait as well as other fine-scale oceanographic features i.e. eddies and meanders that are important to transportation and mixing of planktonic organisms. These physical and biological connections mean that model development for this region needs to carefully consider the placement of the domain boundary and the approach used to implement boundary conditions. Depending on the research question of focus, the Pacific Arctic, or entire Arctic Ocean may need to be considered on some level (coarse resolution) when exploring the dynamics of biological and chemical constituents in the regional northern seas of interest at finer resolution.

Expected changes over the next 3-4 decades

Multiple models with alternative projections for the future state of the Arctic climate system exist (IPCC) and it is not possible to know which of these realizations will become a reality. While each climate model predicts warming to different extents and has different magnitudes of stochastic variability, taken together in ensemble the models predict a robust long term warming trend. Because of the uncertainty in future climate, any prediction of marine ecosystem response in the Bering, Chukchi and Beaufort Seas should also have an envelope of uncertainty associated with them - due both to the uncertainty in atmospheric forcing but also to uncertainties inherent in behavior of the biological organisms in question. Projections of marine ecosystem response should therefore take into account both of these uncertainties. Ideally, an ensemble suite of ecosystem projections would be developed that would permit likelihood of events to be estimated and uncertainty to be quantified.

Ecosystem Services, Socioeconomics, And Impacts Of Change On Local Communities

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Healthy Arctic ecosystems are of fundamental economic, cultural and spiritual importance to arctic indigenous residents. The Arctic environment is changing at an unprecedented rate, characterized by an increase in storm surges, surface temperatures, changes to erosion rates, precipitation rates, as well as changes in species distribution and sea ice coverage (NOAA 2011; SNAP 2008; IPCC 2007). These changes add complexity to the relationships people have with the environment. Within the next two pages this paper will attempt to highlight the main concepts within ecosystems services and state of socio-economics within the Beaufort, Chukchi and northern Bering Sea which should be considered and included in the creation of an Arctic conceptual ecosystem model.

Earth systems are comprised of Arctic terrestrial, marine, and freshwater habitats, with biological and physical components (biogeophysical interactions), and people (Murray et al. 2010). In recognizing that people are part of this system one must also include the social and cultural systems found within the Arctic. For the purpose of this paper Ecosystem Services will be recognized as outcomes of natural environmental process that affect people.

The interactions between and within biogeophysical and human environment creates a positive feed back loop, in which A causes B and in turn B causes A. The resulting changes in dynamics alter ecosystem services, which modify human behavior and outcomes (Chapin et al. 2005). For example, within Inuit Traditional Knowledge it is understood that ice is a common abiotic feature interacting and affecting all other subsystems. While the culture evolved to survive within an environment dominated by ice, people developed knowledge and traditions of how to use ice for transportation, storage, water, protection, among others. As the ice thins and changes, the knowledge and relationship held between the culture and the ice will change. As a result hunting strategies change. Hunting strategies include multiple social and cultural characteristics, such as education, language, etc. This example stresses the complexity of interlinking and overlapping Arctic systems.

Ecosystem services which benefits humans have been summarized within four generalized categories: provisional (e.g., food), regulating (e.g., water filtration), support (e.g., biomass production) and cultural (e.g., knowledge systems, Millennium Ecosystem Assessment 2003). All four categories are inter-connected through the Arctic food web. Creating a model through a food web lens will allow for one to incorporate both social and natural science systems in addition to traditional knowledge (ICC-AK. 2012).

Cultural services include those services important for values, spirituality and the basis of social interactions and organization (Daniel et al. 2012). They may include expression of culture through dance and song, the passing of knowledge, knowledge systems and sharing systems. In the Arctic, these cultural elements intertwine throughout the planning, collection, processing, and storage of food, and shared in a methodical way. Today concern lies in maintaining the integrity of these cultural services, with many conversations focused on the loss of language and interruption of hunting, fishing and gathering practices. Cultural services are also directly impacted by changes in provisional and supporting services, for example the timing of migrations or changes in supporting services could impact when harvest preparations and practices occur.

Overall provisional services provide immediate material for day-to-day survival such as, food, fuel, and water (Fisher et al. 2009). Today multiple stressors are affecting provisional services, from change in atmosphere and water temperature, change in ice coverage to an increase in storm surges, and outside competition for resources (Chapin et al. 2005). For example, communities are observing changes in species distributions, size and health of species. Additional concerns include the quality of drinking water due to pollutants and/or inadequate sewage and water treatment mechanisms. Supporting services directly affect provisional services.

Supporting services are necessary for the production of all other ecosystem services. For example, biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, and water cycling (Rodríguez 2010). Today there is concern regarding the stability of these services as a result of anthropogenic induced climate change, increased stressors on food web dynamics resulting in a change to nutrient cycling and habitat destruction. For example, drying meat or fish is a common way of storing food. The drying of food requires particular air temperatures and precipitation rate. With changes occurring in temperatures, many people are expressing difficulty in being able to dry meat in time (before a storm surge occurs) or that high temperatures cook the drying meat before it has an opportunity to dry.

Regulating services provide mitigation of natural hazards such as protection from storm surges, erosion control and water purification. Increasing erosion rates are causing concern for many villages. The loss of ground and soil integrity affects housing structures, transportation systems, and potentially leads to changes in water chemistry affecting the food web. Regulating services affect all other systems. For example, the timing of fresh water surge along a river has been noted to impact the availability of wood by users downstream that is used for heating and structure (e.g., fish drying racks on treeless delta, Jones 2013).

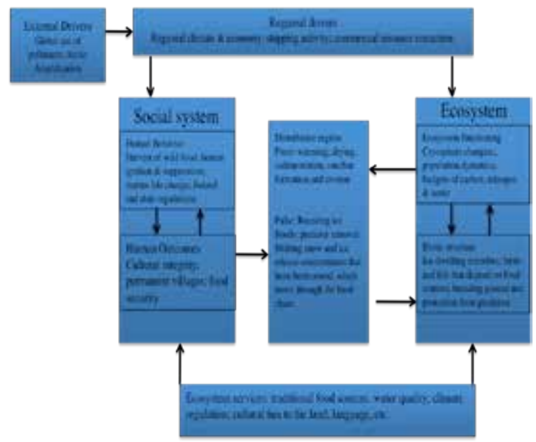

Figure 1. Arctic social-ecological system. Adapted from Chapin et al. 2005

Hunting, fishing and gathering also depends on variability and access. It is customary to move from one food source to another in order to not apply access stress on one species. Rules and customs surround the timing of harvest and the extent of harvest have been built into the knowledge systems that fall under cultural services. Biodiversity is supported through this historic regulatory process and practices. As the earth continues to change over the next fifty years (SNAP 2008), all of the subsystems will also change, changing both ecosystem services and socio-economics.

Arctic villages rely on an economy structure, which includes cash and traditional food sources. Monetary means are often required for housing, electricity, fuel, among others. The importance of these commodities plays a direct impact on the ability to obtain traditional food sources. For example, hunting a whale requires ammunition, fuel, and water vessels. Additionally, while many people still prefer to store whale meat in ice cellars, kept frozen from permafrost, today have to store the meat in freezers run on electricity, increasing the need for money.

The resilience and sustainability of the subsystems identified in this paper could be further complicated by the cumulative effects of climate change impacts acting on ecosystem services in the Arctic. In isolation, impacts on ecosystem services may be negligible; however, the combined, incremental impact of these effects could be consequential. For example, the loss of large areas of sea ice represents habitat loss for seals, microbial communities, affecting species throughout the food chain. The change in seal habitat, driven by changing weather patterns, and accessibility, etc., are all compounding traditional hunting that also interferes with traditions surrounding seal hunting such as celebrations of a boy's first seal into manhood or sharing first blubber with elders.

A gap lies in understanding the threats to resilience and sustainability, the inclusion of Traditional Knowledge, and socio-economic indicators identified by village residents. This being said plenty of information on ecological services and socio-economics of Arctic communities does exist and can be incorporated into ecosystem models. It is suggested that the group become familiar with socio-ecological systems, be open to how Traditional Knowledge may be incorporated and to allow for flexibility. Three papers are listed below to aid in becoming more familiar with these topics.

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APPENDIX D
Developing a Conceptual Model of the Arctic Marine Ecosystem

April 30 – May 2, 2013
Indian Treaty Room
Eisenhower Executive Office Building
Washington, DC

Draft Agenda

Workshop Goals: Diminishing sea ice cover and ocean acidification are altering the Arctic Ocean ecosystem and contributing to substantial economic and cultural changes in the region. The significance of those changes has been highlighted in the United States—where the Arctic Ocean was identified as one of the nine priority objectives in the National Ocean Policy—and internationally by the Arctic Council which is working cooperatively in the Arctic on ecosystem based management, oil spill prevention and response, and search and rescue. Federal research in the Arctic is coordinated by the Interagency Arctic Research Policy Committee (IARPC) as detailed in its five-year Arctic research plan. Twelve implementation teams are working to ensure that the plan's milestones are completed. One of those teams is charged with coordinating studies of the Arctic marine ecosystem and how it is likely to change in the face of global climate change, offshore energy exploration and development, and increasing acidification. **The goal of this workshop is to develop a conceptual model of the Arctic marine ecosystem and to develop hypotheses about how that system is likely to change in the coming decades.**

Specific Objectives: The workshop aims to meet the following objectives;

- Generate a limited number of future scenarios (out to 2050) that the workshop participants expect to evolve from the effect of natural and anthropogenic stressors on the current US Arctic marine ecosystems;
- Develop a set of testable hypotheses to better understand and predict the effect of these changes on the marine ecosystem and its components, as a way of better understanding which scenarios may actually emerge over the next few decades;
- Design of an overarching, hypothesis driven, future marine Arctic conceptual model that can become the basis for a coordinated research program.

Tuesday April 30, 2013

9:00 Welcome and Introductions
John Holdren
Assistant to the President
Director of the Office of Science and Technology Policy

9:30 Purpose and Rationale of the Workshop
Brendan Kelly
Assistant Director, Polar Science, Office of Science and Technology Policy

Alan Thornhill
Director of the Office of Science Quality and Integrity, U.S. Geological Survey

SESSION 1 – The Current System

9:45 Introduction of the Strawman conceptual model of the modern day system
Francis Wiese
North Pacific Research Board

10:15 *Coffee Break*

10:45 Perspectives and Discussion of 2-page Subject Papers
Moderated by Brendan Kelly

Physical Drivers and Feedbacks
Rebecca Woodgate
Jim Overland

Biological Oceanography
George Hunt

Benthos
JoLynn Carroll

12:00 *Lunch (On own)*

1:30 Perspectives and Discussion of 2-page Subject Papers (Continued)

Moderated by Brendan Kelly

Fish, Birds and Mammals

Mike Sigler

Richard Glenn

Hotspots

Jane Lubchenco

Anthropogenic Stressors

Ian Perry

Henry Huntington

3:15 *Coffee Break*

Ecosystem Services

Mike Fogarty

George Noongwook

Linkages

Amanda Lynch

5:00 *Adjourn*

Tour of the Eisenhower Executive Office Building

6:00 *Reception*

Indian Treaty Room

Wednesday May 1, 2013

SESSION 2 – Developing Future Scenarios

Generate a limited number of future scenarios (out to 2050) which you expect to evolve from the effect of natural and anthropogenic stressors on the current US Arctic marine ecosystem.

9:00 Future Scenarios Panel and Discussion
Francis Wiese, *Moderator*

James McCarthy
Jim Kennett

10:30 *Coffee Break*

Future Scenarios Discussion Continued

12:00 *Lunch Break* (*On own*)

SESSION 3 – Developing Testable Hypothesis

Develop a set of testable hypotheses to better understand and predict the effect of these changes on the marine ecosystem and its components, as a way of better understanding which scenarios may actually emerge over the next few decades.

1:30 Testable Hypothesis Panel and Discussion
Brendan Kelly, *Moderator*

Carlos Duarte
Tim Lenton

3:15 *Coffee Break*

SESSION 4 – Developing a Conceptual Model

Design an overarching, hypothesis driven, future marine Arctic conceptual model that can become the basis for a coordinated research program.

3:45 Develop Outline for a conceptual model
Francis Wiese, *Moderator*

5:15 *Adjourn*

Thursday May 2, 2013

SESSION 4 – Developing a Conceptual Model (Continued)

9:00 Breakout Drafting Teams based upon outline

10:15 *Coffee Break*

10:45 Breakout Groups Resume

12:00 *Lunch*

1:30 Reports from Working Groups and Discussion
Brendan Kelly, *Moderator*

3:00 *Coffee Break*

3:30 Consolidate Sections and Finalize Conceptual Model
Francis Wiese, *Moderator*

5:00 *Adjourn*

5:30 Informal no-host, post-workshop gathering (near EEOB)

Group 1 Leader: Henry Huntington Staff: Danielle Dickson Rapporteur: Dee Williams Room # ?	**Group 2** Leader: Amanda Lynch Staff: Sara Bowden Rapporteur: Martin Jeffries Room # ?
Group 3 Leader: Jim Kennett Staff: Melissa Russ Rapporteur: Guillermo Auad Room # ?	**Group 4** Leader: Mike Sigler Staff: Neil Swanberg Rapporteur: Richard Merrick Room # ?

APPENDIX E
Developing a Conceptual Model of the Arctic Marine Ecosystem

April 30 – May 2, 2013
Indian Treaty Room
Eisenhower Executive Office Building
Washington, DC

Agenda as Executed
2 May 2013

Workshop Goals: Diminishing sea ice cover and ocean acidification are altering the Arctic Ocean ecosystem and contributing to substantial economic and cultural changes in the region. The significance of those changes has been highlighted in the United States—where the Arctic Ocean was identified as one of the nine priority objectives in the National Ocean Policy—and internationally by the Arctic Council which is working cooperatively in the Arctic on ecosystem based management, oil spill prevention and response, and search and rescue. Federal research in the Arctic is coordinated by the Interagency Arctic Research Policy Committee (IARPC) as detailed in its five-year Arctic research plan. Twelve implementation teams are working to ensure that the plan's milestones are completed. One of those teams is charged with coordinating studies of the Arctic marine ecosystem and how it is likely to change in the face of global climate change, offshore energy exploration and development, and increasing acidification. **The goal of this workshop is to develop a conceptual model of the Arctic marine ecosystem and to develop hypotheses about how that system is likely to change in the coming decades.**

Specific Objectives: The workshop aims to meet the following objectives;

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- Develop a set of testable hypotheses to better understand and predict the effect of these changes on the marine ecosystem and its components, as a way of better understanding which scenarios may actually emerge over the next few decades;
- Design of an overarching, hypothesis driven, future marine Arctic conceptual model that can become the basis for a coordinated research program.

Tuesday April 30, 2013

9:00 Welcome and Introductions

Brendan Kelly
Assistant Director, Polar Science, Office of Science and Technology Policy

9:30 Purpose and Rationale of the Workshop

Brendan Kelly
Assistant Director, Polar Science, Office of Science and Technology Policy

Simon Stephenson
Director, Arctic Sciences, National Science Foundation

Alan Thornhill
Director of the Office of Science Quality and Integrity, U.S. Geological Survey

Francis Wiese
Science Director, North Pacific Research Board

Questions & discussion

10:30 *Coffee Break*

SESSION 1 – The Current System

11:00 Introduction of the Strawman conceptual model of the modern day system
Francis Wiese
North Pacific Research Board

12:00 Perspectives and Discussion of 2-page Subject Papers
Moderated by Brendan Kelly

Physical Drivers and Feedbacks
Rebecca Woodgate
Jim Overland

12:30 *Lunch (On own)*

2:00 Perspectives and Discussion of 2-page Subject Papers (Continued)
Moderated by Brendan Kelly

Hotspots
Jane Lubchenco

Biological Oceanography
George Hunt

Benthos
JoLynn Carroll

3:45 *Coffee Break*

4:00 Perturbations
Henry Huntington

Linkages
Amanda Lynch

4:45 Discussion and Recap

5:00 *Adjourn*
Tour of the Eisenhower Executive Office Building

6:00 – 8:00 *Reception*
Indian Treaty Room

Wednesday May 1, 2013

9:00 Recap of day 1 and plan for day 2
Products from Workshop

9:30 Remarks and conversation with Dr. John Holdren,
Assistant to the President and Director of the Office of Science and Technology Policy

9:45 Perspectives and Discussion of 2-page Subject Papers (Continued)
Moderated by Brendan Kelly

Fish, Birds and Mammals
Mike Sigler
Richard Glenn

Anthropogenic Stressors
Ian Perry
Henry Huntington

10:45 *Coffee Break*

11:00 Ecosystem Services
Mike Fogarty

SESSION 2 – Developing Future Scenarios

Generate a limited number of future scenarios (out to 2050) which you expect to evolve from the effect of natural and anthropogenic stressors on the current US Arctic marine ecosystem.

11:45 Future Scenarios Panel and Discussion
Moderated by Francis Wiese

Jim Kennett – *Paleo perspectives*
James McCarthy

12:30 *Lunch Break* (*On own*)

2:00 Future Scenarios Panel and Discussion *Continued*

Breakout Groups – *Scenario investigations*
Assuming current trends continue, how will aspects of the ecosystem or ecosystem services change by 2050?
Walrus
Bowhead whales
Regulating services (i.e., natural ecosystem drivers)
Ecosystem services and marine access

SESSION 3 – Developing Testable Hypothesis

Develop a set of testable hypotheses to better understand and predict the effect of these changes on the marine ecosystem and its components, as a way of better understanding which scenarios may actually emerge over the next few decades.

4:00 Testable Hypothesis Panel and Discussion
Moderated by Brendan Kelly

Carlos Duarte – *hypothesis development*
Tim Lenton – *tipping points*

5:30 *Adjourn*

Thursday May 2, 2013

SESSION 3 – Developing Testable Hypothesis *Continued*

Moderated by Brendan Kelly

9:00 Plan for the day

9:10 Your ONE most burning question!

10:00 Breakout Groups – *testable hypotheses development*
Sea ice
Ecosystem structure and function
Hotspots and productivity
Ecosystem services

11:00 Reports from Working Groups and Discussion

12:00-12:30 Catered lunch

12:30 Further discussion on hypotheses

SESSION 4 – Developing a Conceptual Model

Design an overarching, hypothesis-driven, future marine Arctic conceptual model that can become the basis for a coordinated research program.

1:00 Conceptual model framework
Moderated by Francis Wiese

2:00 Breakout groups on conceptual model development
Process study framework for spring, summer, fall (daylight available)
Process study framework for winter (light-limited)
Approaches to ecosystem research (multi-layer model, perturbations to ecosystem services)
Management and policy

3:00 Reports from Working Groups/Discussion
Moderated by Brendan Kelly

3:45 Next steps – discussion about developing products

4:00 *Adjourn*

5:00 Informal no-host, post-workshop gathering (near EEOB)

APPENDIX F

List of research questions and hypotheses provided by participants throughout the course of the workshop*

Questions

Sea ice

1. What are the mechanisms driving—and consequences of—the changing seasonality of sea ice extent and thickness?
2. Is there still a defined ice edge?
3. Is the current mix of seasonal and multiyear sea ice unstable? When the entire region's ice cover is seasonal, will that be a stable state?
4. How will the decline in summer sea ice cause a shift in the dominant species in the ecosystem?

Ecosystem structure and function

1. What are the likely impacts of changes in flow of water through the Bering Strait?
2. What process are setting flow, water properties, and stratification in the system; what are their global and regional drivers and timings; and what aspects of their change have the greatest impact on the ecosystem? Can we bound future change?
3. What are the structural and process backbones that hold the ecosystem together and what are the tipping points that will lead to the breaking of the current ecosystem?
4. The paleo record provides evidence for the evolution of the Arctic system in response to punctuated episodes which uniquely control the Arctic. During resetting, especially the early part of deglaciation, how similar are interglacial ecosytems in structure and function, and how robust are they to change?
5. How do we, in a management context, retain the resilience of the social-ecological system to unexpected changes?
6. What is more important, Arctic secondary production or advected subarctic secondary production?
7. Does winter reset conditions in the Chukchi Sea? In the Beaufort Sea? Can we have a Northern Bering Sea annex?
8. Can we distinguish expected interannual variability from long-term trends?
9. What taxa will have the greatest effect on the food web?
10. Are there critical species for which (local and regional) functional extinction will lead to a regime shift in ecosystem structure, process or service? Are there key diagnostic traits to what those species are?
11. What is the importance of the partitioning of primary production ?
12. What is/are the cues triggering the major events setting up the Arctic ecosystem: light, temperature, biogeochemical (pH or pCO_2) or biochemical clues?
13. Can offsets in seasonal clues lead to mismatches decoupling ecosystem processes?
14. What are the ceilings to primary production in an open-water Arctic?
15. Is top-down control a major control mechanism in the Arctic?
16. Will incoming top predators lead to increased top down control of ecosystem processes/services?
17. Are top predators (extant or incoming) functionally redundant?
18. Is the Arctic food web structurally prone to cascading top-down effects? Which are the critical nodes?
19. The arctic ecosystem presents a number of alternative stable configurations, with transitions triggered by climatic drivers. Based on this:
    i. Can the palaeorecord and historical records help identify stable ecosystem configurations in periods of warming and cooling? (e.g. early Holocene as proxy for forthcoming Arctic)

* Participants were given the opportunity to submit ideas throughout the workshop. The ideas listed here were not all discussed and do not represent the consensus of the group.

ii. Can shifts in species trigger cascading effects that lead to shifts to an alternative state?
iii. What are the buffers holding the systems in the alternative stable states? Are these buffers amenable to management action?
iv. Are there robust leading indicators of the proximity of thresholds for the transition across alternative states?
v. Are key thresholds modulated by pressures or are they static over time?

Hotspots and productivity

1. Are hotspots mostly determined by topography and, thus, unlikely to be altered by climate changes?
2. How will physical forcing cascade through pelagic-benthic coupling?
3. What controls productivity at all levels of the ecosystem, and how are these processes affected by anthropogenic activities?
4. In the face of a highly unpredictable system, which areas are most important and biologically valuable to protect from cumulative human impacts?
5. What are the physical drivers of hot spots (for ecosystem structure, process or services) in the Arctic? Are these place-based or spatially variable?
6. What is the cumulative distribution of Arctic hot spots? Are the sum of small and low-intensity hot spots comparable to that of unique large and intense hot spots?

Hot Moments

1. Is the spring phytoplankton bloom triggered by the onset of a critical irradiance threshold?
2. What is/are the clues triggering the major events setting up the Arctic ecosystem: light, temperature, biogeochemical (pH or PCO2) or biochemical clues?
3. Can offsets in seasonal cues lead to mismatches decoupling the ecosystem?
4. Are persistent organic pollutant loads constraining the adaptation and micro-evolutionary potential of Arctic organisms?
5. What events drive the sourcing of key organisms (e.g. copepods) to the system?
6. Are there critical periods (*hot moments*) in the Arctic ecosystem where key organisms and processes are particularly vulnerable or resistant to perturbations (e.g. noise, oil spills, etc.)?

Ecosystem Services

1. In what ways, at what scales, and where, do human activities in the Arctic marine region affect the structure or functioning of the ecosystem, services provided by that ecosystem to humans, or access by humans to those ecosystem services?
2. Defining "risk" as the product of likelihood and impact, what are the biggest risks to the ecosystem and the services it provides and how do we reduce those risks?
3. What surprises might be anticipated that would be the most challenging to deal with, and what can we do to anticipate those or create a buffer to mitigate their effects?
4. Are (all?) ecosystem services idiosyncratic? If so, who are the key species supporting them? Are there cryptic components of realized or potential ecosystem services?
5. Are key Arctic communities resistant to removal of top predators?
6. What is the excess production that can be sustainably harvested through fisheries?

Surprises

1. Are there Arctic "time bombs" that can trigger rapid change is Arctic ecosystems?
2. Are social (opinion shifts, technology, etc.) and political responses able to greatly switch the trajectory of the Arctic ecosystem?

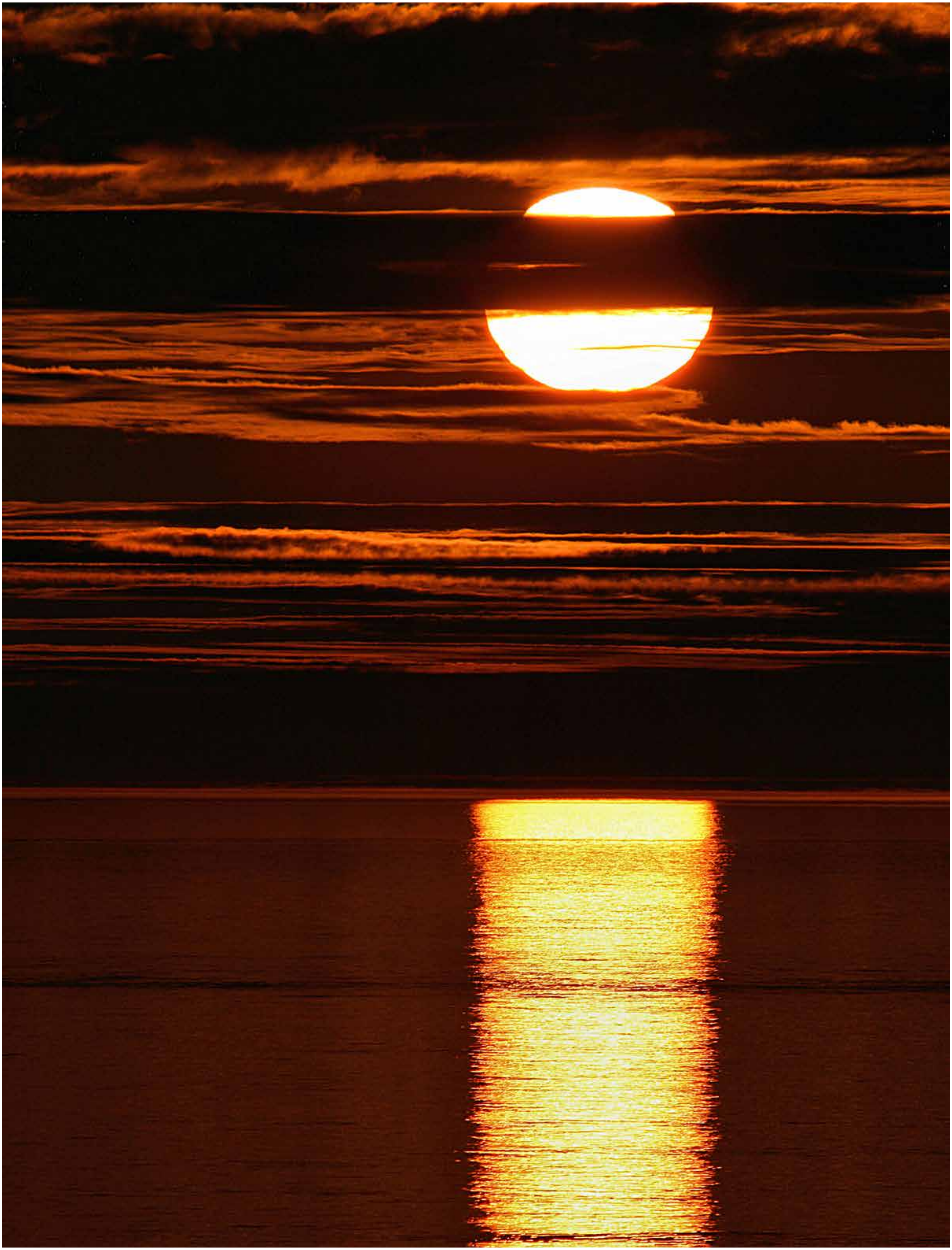
<u>Hypotheses</u>

Ecosystem structure and function

1. Arctic productivity will remain dominated by timing and distance of ice retreat and fluxes of source water from the Bering Sea and the Arctic Basin onto the shallow shelves of the northern Bering, Beaufort and Chukchi seas. The region will remain a benthic-dominated system because ice will continue to form each winter. The lengthened ice-free period will lead to increased primary and secondary productivity. Planktivorous species will benefit. Ice-affiliated species currently dependent on ice during summer will face open water instead and decline; however ice-affiliated species dependent on ice during spring will be less affected.
2. Climate-induced changes in ocean physics and chemistry will modify prey availability and partitioning, the intensity of predator-prey relationships and the location of zoogeographic provinces through bottom-up processes.
3. More pelagic production falls to the seafloor in the Arctic than at lower latitudes. This strong benthic-pelagic coupling results in part from sea ice primary production, which occurs too early in the year to be utilized by undeveloped zooplankton communities.
4. The Chukchi and Beaufort shelves are controlled by bottom-up processes including primary production in the northern Bering Sea that is advected into the Chukchi Sea. However top-down control occurs in some cases.
5. Climate and ocean conditions influencing circulation patterns and domain boundaries will affect the distribution, frequency and persistence of fronts and other prey-concentrating features and thus the foraging success of marine birds and mammals largely through bottom-up processes.
6. Decoupling of planktonic/benthic productivity through sea ice loss will cause a reduction in benthic productivity.
7. The Arctic has exhibited alternative stable configuration related to different climate modes.
8. The loss of sea ice diatom productivity will not be compensated by other groups and hence fundamentally change the Arctic ecosystem.
9. Loss of keystone sea ice taxa will accelerate ecosystem change in the Arctic
10. The marine paleocological record suggests an inherent robustness of the modern Arctic ecosystem to major changes in seasonal sea ice extent.
11. The present sea ice system is unstable, but a future Arctic-wide seasonal sea ice cover will have a stable annual cycle.

Ecosystem services

1. Regional human activities will not affect the coarse-scale structure or functioning of the marine ecosystem, but will have localized impacts from direct disturbance of habitats and species.
2. Any coarse-scale ecosystem impacts will result from catastrophic/episodic events such as an oil spill or the introduction of an invasive species.
3. Regional human activities will not affect the overall provision of ecosystem services in the region, unless catastrophic impacts occur.
4. Regional human activities will interfere with regional/local access to ecosystem services, through conflicts in space and time.
5. Local human responses will be constrained by regulatory inflexibility and the location of infrastructure, reducing adaptive capacity.
6. The areas where space/time conflicts will be most severe are the Bering Strait and the mid-Beaufort coast.
7. Climate-ocean conditions will change and thus affect the abundance and distribution of subsistence hunting and fishing.



Lisa Langell