The Aleutian-Bering Climate Vulnerability Assessment

Final Report

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EXECUTIVE SUMMARY

Recent efforts to develop downscaled climate projections for the Bering Sea and Aleutians created an opportunity to better assess regional vulnerability to climate change. The Aleutian Bering Climate Vulnerability Assessment (ABCVA) was launched in 2014 to bring together regional science expertise and stakeholder interests in a rapid evaluation of the implications of future climate projections. This effort followed an internationally accepted but flexible pathway to develop practical, priority research topics that address ecosystem and community vulnerabilities. The ABCVA was completed as a partnership between the Aleutian and Bering Sea Islands Landscape Conservation Cooperative (ABSI LCC), the Alaska Climate Science Center and the Alaska Ocean Observing System (AOOS), and ultimately brought together three linked objectives:

1. identify and assess selected climate vulnerabilities of key resources and ecosystem services in the Aleutian Islands and Bering Sea region
2. broadly engage managers and stakeholders about the implications of climate vulnerabilities in the region
3. help ABSI LCC and the Alaska Climate Science Center and AOOS prioritize future research investments and focus

The ABCVA convened a group of 30 researchers with expertise ranging from anthropology to zooplankton to review climate projections and their implications for the Aleutians and Bering Sea. These experts worked in five topic-based teams to assess vulnerabilities of species and ecosystem services relative. Each team identified initial vulnerabilities and made recommendations for further research that would help managers and communities better understand the implications of the changing climate in this region.

In a subsequent rapid synthesis effort members from the expert team used a Structured Decision Making process to rank species that may be most vulnerable to climate change and the key drivers of change affecting those species. They also used this process to collectively prioritize 35 research topics and categorize them by cost category for potential future action by ABSI LCC, the Alaska Climate Science Center, AOOS and ideally other management and science organizations working in the region. Examples of some high priority research topics identified by this assessment in the cost category of <$100,000 included:

- Using existing projections to explore shift in distribution and timing of primary and secondary productivity in key areas for marine mammals with restricted mobility
- Understanding climatic thresholds that prevent the spread of pathogens/parasites important to marine species and human communities
- Baseline data layers for coastal cultural sites and coastal infrastructure to explore exposure based on hindcasts of storms and/or projected storminess
- Better understanding of body condition of young of the year for (e.g., fish species or marine mammals) to understand climate effects on bioenergetics
- Using coupled ocean/climate model projections for comparison to seabird population dynamics models to explore impacts at regional scales

Collectively our team identified indirect effects of ocean acidification; direct effects of sea ice extent; indirect effects of changes in ocean temperature; and direct effects of changes in winds/storminess as climate change, or related drivers likely to have the greatest potential impacts on species in the region. They also identified a suite of species of particular concern relative to these drivers including: walrus and sea otters; diving, piscivorous seabirds (like the Tufted Puffin); and key commercial and subsistence fisheries species like the Atka mackerel, red king crab, salmon, and pollock. Further, the team focused on seabirds developed an analytical process to explore change in projected climate variables for Important Bird Areas recently delineated in the Bering and Aleutians. An initial pilot of this process identified several areas where projected declines in benthic invertebrates may have impacts to sea duck species of conservation concern including the Steller 's Eider.

Results from this work were shared during a focused, public session held within the regional hub community of Unalaska/Dutch Harbor where structured insights about climate change were collected from local residents. The results of this project have also been shared at several other local, regional, and national conferences to broaden awareness about climate change issues for this region. Further investments in communication have included developing a downloadable 'interactive' that tells the story of this project from motivation and methodology to process and results. An additional lasting legacy of the ABCVA is a catalog of online content hosted on the AOOS Arctic Portal where spatially explicit projections for climate and ecosystem variables are available to visualize and download.

This work brought together novel collaborations between residents, stakeholders, scientists, and natural resource managers in the region. We hope this project might serve to launch new and diverse partnerships to further address challenges related to climate change in Bering Sea and Aleutians.

Chapter 1: Introduction: The Aleutian and Bering Sea Climate Vulnerability Assessment (ABCVA)

Aaron Poe, Tom Van Pelt, Jeremy Littell, Ellen Tyler and Nick Bond

Introduction

The Aleutian and Bering Sea Islands (ABSI) region (Figure 1) supports an exceptionally rich and productive marine ecosystem, including several species of marine mammals and seabirds identified by managers and stakeholders as conservation priorities. The high biological productivity of this region is reflected in the prolific commercial fisheries that account for half of the total U.S. seafood landings. This ecosystem, including both marine and terrestrial components, is also vital to the subsistence culture of some of Alaska's most isolated communities. The venerable and proud heritage of these communities and the unique history of the region are also reflected in a diverse network of archaeological sites.

Yet the remoteness of this region has not spared it from widespread threats related to climate change and other environmental stressors. In 2013 the Aleutian and Bering Sea Islands Landscape Conservation Cooperative (ABSI LCC), in collaboration with the Alaska Climate Science Center, completed a Strategic Science Plan (SSP; available at http:/ABSILCC.org) that identified climate change as the primary landscape-scale environmental stressor affecting this region. This SSP identified possible impacts on conservation priorities commonly identified in numerous research and management plans from the region. These plans identify a number of iconic species, including those that are of keen interest to federal and state managers as well as species vital to social, cultural, nutritional and economic wellbeing of communities in the region. Another category of conservation priority identified in the ABSI LCC's SSP includes sites and artifacts that tell the story of the region's cultural heritage. Potential impacts to the broader system of the region were also addressed as *ecosystem services* as described by the Millennium Ecosystem Assessment in 2005.

In 2013, the SSP was used as a basis to establish a partnership with the Alaska Climate Science Center and the Alaska Ocean Observing System (AOOS) to conduct an initial assessment of climate change implications for these resources and services-- the **Aleutian Bering Climate Vulnerability Assessment (ABCVA)**. These three entities came together with the following objectives:

1. identify and assess selected climate vulnerabilities of key resources and ecosystem services in the Aleutian Islands and Bering Sea region
2. broadly engage managers and stakeholders about the implications of climate vulnerabilities in the region
3. help ABSI LCC and the Alaska Climate Science Center and AOOS prioritize future research investments and focus

Together we aimed to complete a rapid (e.g., approximately one year) project that would achieve the above goals in order to identify subsequent collaborative efforts that could be initiated in the near term. The three entities leading this ABCVA, funded primarily by the U.S. Department of the Interior and the National Oceanic and Atmospheric Administration (NOAA), have similar goals of providing applied scientific information about climate change to managers and stakeholders. For this effort the focus on was on issues of interest to these audiences within the extent of the ABSI LCC region (Figure 1). Though this was the general focus area, we recognized that climate change issues transcend boundaries and considered this a 'soft' boundary when framing the assessment.

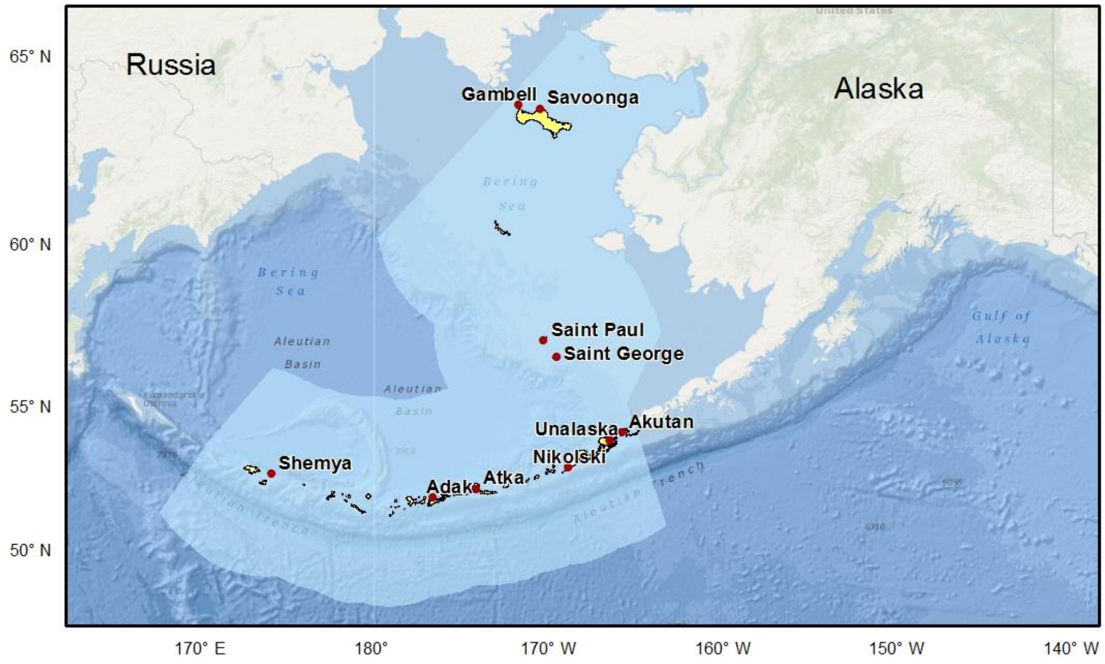

Figure 1. The boundary (light blue polygon) of the study area for the ABCVA project. This is also the boundary for the Aleutian and Bering Sea Islands Landscape Conservation Cooperative.

Projected Climate Change

What follows is a brief introduction to key drivers associated with climate change in the ABSI region. Expanded discussion each and the origins of their projected future states are provided in chapter 2.

Atmospheric Conditions

The Aleutian Islands and Bering Sea region can anticipate warmer air temperatures – about 1.8-3.6°F (1 – 2 °C) averaged across the region -- by the middle of the 21st century (e.g., 2030-2059) compared to the late 20th century (e.g., 1970-1999), with a greater rate of warming in winter than in summer. As revealed by some of the model results in chapter 2, there should be fewer extremely cold days (arbitrarily defined as those with average temperatures < 24.8°F (-4° C)) and many more warm days (defined as those with average temperatures > 53.6°F (12° C)). The latter types of days have occurred very rarely in the past, but can be anticipated to occur routinely –about 20 times a summer -- by the middle of the century.

Projected precipitation rates, changes in seasonal storminess, and changes in wind are variable across different climate models. To account for this variation, multiple model projections for the same time period are averaged to describe expected future conditions. On average, climate models project about 10-20% greater precipitation by the middle of the century with a slight increase in the incidence or strength of extreme events (storms) in the autumn, and a slight decrease in winter storminess.

Oceanic Conditions

Mean upper ocean temperatures are expected to increase by roughly 2.7°F (1.5° C) by mid-century (Hermann et al. 2013). The magnitude of this warming will be affected by possible changes in cloudiness, especially during summer. This effect is included, but not necessarily properly represented, in current climate models, and therefore is a source of potential error in their projections. The models also indicate a decrease in evaporation relative to precipitation, i.e., a freshening of the near surface waters of the North Pacific including the Bering Sea (Capotondi *et al.* 2012). Along with the greater warming near the surface versus at depth, this change will serve to stratify the upper portion of the water column. The magnitude of this increase during summer ranges from about 10 to 40% among different climate models. An important implication of this increase in stratification is a likely reduction in the vertical flux of nutrients from depth into the upper part of the water column in summer, with a decrease in primary production during this time of year as a result. This change will probably not be manifested in the shallow (< 50 m) portion of the Bering Sea shelf, or in the vicinity of the Aleutian Islands and especially their passes, where tidal currents are sufficient to maintain a well-mixed water column.

Some coupled ocean-atmosphere models incorporate explicit treatment of ocean currents, but their coarse resolution means that they cannot adequately reproduce the details in the flows that occur near prominent features of the bathymetry such as the Aleutian Island chain. Higher-resolution numerical ocean model results are available (some examples based on the work by Hermann *et al.* 2013 are posted on the aforementioned website maintained by AOOS), but are still limited in their ability to capture flow through Aleutian passes and in the immediate vicinity of other barriers. On larger scales, the models as a group suggest that, at least over the next few decades, systematic changes in the gyre circulations will not exceed the historically observed "noise" due to climate variability.

Sea Ice

Sea ice helps to define the ecosystem of the Bering Sea. It begins forming in the northern Bering Sea as early as November and may remain into June of the following year. Sea ice forms in the northern portions of the shelf and is then blown southward by prevailing winds into areas of warmer water where it begins to melt. This process affects water temperature, salinity and ocean currents and is critical to the physical conditions that influence the way the Bering Sea ecosystem works (McNutt 2012). The ice itself provides habitat for everything from microorganisms to birds and the region's marine mammals but more importantly its presence directly relates to the timing of the spring phytoplankton bloom that is the cornerstone of the Bering Sea ecosystem. Without ice after mid-March, the spring bloom does not occur until May or June. This results in maximum zooplankton growth being delayed until later in the season when ocean temperatures are warmer and stratification sets in at upper surface layers providing more nutrients to pelagic species. Primary production from an ice-associated bloom earlier in the year generally falls to the bottom, supporting benthic communities (e.g., Hunt and Stabeno 2002).

Additionally the formation, motion and melting of the ice edge plays an important role in controlling the heat exchanged between the ocean and atmosphere with profound implications on weather including changes in wind speed and direction as well as air temperature. The ice itself can affect the direction of storm tracks as well as storm frequency and intensity. The increase in open-water conditions enhances the probability that strong wind will result in a storm surge, because the presence of ice inhibits wave formation (e.g., Reimnitz and Maurer 1979). Reduction in summer sea ice diminishes reflection of solar energy and creates additional ocean heat storage in newly formed sea ice-free areas. The additional heat stored in the ocean during summer is given back to the atmosphere the following autumn, causing changes in normal patterns of weather and climate variability with global consequences. Recent studies support an increased connection between shifts in Arctic climate with climate variability in mid-latitudes. Such Arctic to mid-latitude connections can be expected to strengthen over the next decades with further sea ice loss (NOAA 2011).

Climate model projections of sea ice for the region have been examined by Wang *et al.* (2012) and indicate a reduction of 40% on average in areal ice extent in spring by the 2050s compared to 20th century observations. Projections of a nearly sea ice-free summer in the Arctic by the end of the century, made just three years ago, have been revised recently and now indicate that ice-free summers may occur as early as the 2030s (Wang and Overland 2012). However, these projections are in contrast with recent observations. During a long-term decrease, occasional temporary increases in summer ice can be expected over timescales as long as a decade due to internal variability (Kay *et al.* 2011). For example, five of the past six years have had greater-than-average ice cover in the Bering Sea and the trends for winter and spring have been positive from 1979-2013 though not statistically significant (Cavalieri and Parkinson 2012). Multiyear to decadal variability in Bering Sea ice cover over the past four decades may actually be masking any underlying trend. The projected reduction of winter sea ice is only about 10%, indicating that the Arctic will shift to a more seasonal sea ice pattern. Though this ice is thinner, it will likely cover much of the same area now covered by sea ice in winter (Rogers *et al.* 2013). As discussed by Stabeno *et al.* (2012), the expected changes in sea ice are apt to be much more dramatic on the southern portion than on the northern portion of the Bering Shelf

Projecting the Future for Vulnerability Assessment
Expectations of the future climate of the region are based primarily, if not completely, on the projections from global climate models and these models are not perfect. They incompletely represent the boundary layers in the upper part of the ocean, lower part of the atmosphere, and other key elements of the physical system. Different models project significantly different outcomes for the region depending on time frame, initial conditions, and other sources of uncertainty. Since it is inadvisable to pick or weight the various models with regards to the reliability of their projections (Pierce *et al.* 2009, Knutti *et al.* 2010), it is prudent to adopt an ensemble approach (e.g., Overland *et al.* 2011) and consider the potential range rather than a single scenario. Dynamical downscaling with higher-resolution numerical models, some of which feature modules for biogeochemical variables, is increasingly being employed for terrestrial and marine ecosystem applications. In general, while these models are becoming more realistic, they are still at the stage where they are probably better used for exploring the sensitivities in a particular system, and potential transitions in structure and function, rather than for making specific predictions on multi-decadal time horizons.

Methods

As the three contributing partners, ABSI, the Alaska Climate Science Center and AOOS established a core team of four individuals to oversee the assessment. This 'core team' recruited and coordinated the efforts of a group of 26 experts (Table 1) who generously volunteered their time to assess potential effects of climate change on resources and services in the region. These individuals were chosen based on topical expertise as well as with the intent of having diverse affiliations with research and management entities working with the ABSI region. We were not able to achieve representation from all management and research organizations; instead we strove to have adequate representation to address a majority of key regional issues and resources. This ABCVA expert group worked with the core team across five topic areas:

- Seabirds
- Marine Mammals
- Fish and shellfish
- Terrestrial Vegetation
- Socioeconomic and Cultural Resources

Our core team also secured climate expertise from Dr. Nick Bond (University of Washington and NOAA's Pacific Marine Ecology Lab) and Dr. John Walsh (University of Alaska, Fairbanks) and). Bond and Walsh helped the core team launch the project by presenting a webinar to team members on their recent climate downscaling efforts in the region (e.g., Hermann et al 2013 and Walsh 2008, SNAP 2014). This webinar (available at: https://vimeo.com/82409269) was hosted specifically for our project team but was also advertised broadly to researchers, stakeholders and managers in the region as part of the month series on climate change hosted by the Alaska Center for Climate Change Adaption and Policy. It featured their methodologies and results. It served as an opportunity to for our expert team to get an introduction to the projected states for physical and biophysical drivers in the region. It also served as an opportunity to spread awareness about the upcoming vulnerability assessment project for others interested in climate change in the region.

This webinar was followed by an orientation document that was shared with the expert team. This document (essentially chapter 2 in this volume) provided further detail about the climate projections for the region and some of the data and tools available to explore those projections. This document was shared prior to a facilitated workshop designed for an expert team at the Alaska Marine Science Symposium in 2014. This workshop served as the first opportunity for our expert team to sit down together with our core team to discuss the project as a whole and confirm roles and responsibilities as well as expectations for their participation. It was also an opportunity for further engagement with our climate scientists Bond & Walsh to ask them questions about their approach, discuss uncertainty in the projection results, and see demos of the tools available for use the for this assessment.

During this workshop we broke our experts into five teams following the topic areas above. We asked each team to identify their first preliminary ideas about climate vulnerabilities associated with their topic area based on the information shared by our core team as well as Bond & Walsh. Each group then shared their back their early conclusions with the full team to help identify areas of potential common interest. We identified some challenges relative to how to adequately consider trophic connections, how to consider the interactions of other environmental stressors like ocean acidification or marine vessel traffic.

This expert team workshop was followed by a broader "stakeholder" workshop also held at Alaska Marine Science Symposium. This workshop served to introduce to the effort, including the projections made by Bond and Walsh to the broader science and manager community in the ABSI region. Each of our five expert teams also presented their initial ideas on climate change vulnerabilities associated with their topic areas during this workshop. This workshop and presentations was designed specifically so that our experts could receive feedback from a broader audience that could help them build upon and refine their initial ideas.

Following the workshops the core team provided the expert team with further guidance on the development assessment chapters. We asked them to identify ***which*** species or ecosystem components were likely to be most strongly affected by climate change, and in broad, mainly qualitative terms, explain ***why*** these resources are likely to be vulnerable. Beyond direct expected effects we also asked them to consider any reasonably foreseeable indirect effects resulting from disconnects in trophic function. We also identified important interactions between climate and other environmental stressors (e.g., compounding effects of ocean acidification or the loss of sea ice and increased accessibility of the region for marine vessels).

To complete their chapters our core team suggested the framework laid out by Glick *et al.* (2011) for assessing climate vulnerability with the aim of returning an integrated understanding of vulnerability based on:

- degree of exposure of resources or ecosystem services to climate effects;
- risk to resources or ecosystem services based on exposure;
- and the adaptive capacity of managers & stakeholders.

Through this assessment we asked the expert teams to begin to follow a stepwise process of inquiry structured into five stages:

1) Identifying Important Resources and Services at Risk to Climate Change

In asking experts to focus efforts we ask them to think about species or ecosystem linkages with:

- Well-documented sensitivities to climate change drivers.
- Existing special management zones or protected areas indicative of concentrated distributions of species that might not be able to use other locations.
- Well-documented risks from other conservation threats that might be compounded by climate change.
- Foundational linkages to the socioeconomic wellbeing of communities.
- Vital connections to the trophic function of the region.

2) Evaluating Sensitivity to Climate Change

Following an initial assessment of important resources and services, we asked experts to further refine focus based on species or ecosystem linkages where there are:

- Specific thresholds, physiological or otherwise, where extreme changes in climate variables are a documented concern.
- Specific dependencies on key habitats or sites that might be a special risk.
- Demonstrated links to critical stages of species phenology (e.g,. reproduction or migration) or harvest.
- Expected changes in distribution of species or habitat that might result in availability for harvest or new competitors or predators.
- Species life history or reproductive strategies that result in slow population growth.

3) Evaluating Exposure to Climate Change

Experts were asked to consider the degree to which the focal species or ecosystem linkages they have identified thus far are exposed to stress resulting from climate drivers. They were asked to consider exposure to climate change over the next 40-100 years based on the information provided by Bond and Walsh (see chapter 2) and encouraged to evaluate:

- How resources or linkages might respond to basic physical drivers like temperature, wind, precipitation as well as derived variables like sea ice extent and character, storminess, and frequency of extreme temperature events.
- How these climate variables might vary within the region and where key places of rapid or extreme change might occur.
- If there are changes within key seasons when species or ecosystem linkages might be most vulnerable.
- If other large scale conservation threats may result in increased exposure to climate change.

4) Evaluating Adaptive Capacity

Upon identifying focal resources and ecosystem services and their exposure to climate change we asked the expert teams to consider:

- If the identified species may have inherent, demonstrated capacity to adapt to large-scale changes in habitat qualities based on flexibility in behavior, high level of mobility or what is known about evolutionary history.
- In the context of human communities, if there is evidence of the ability to make rapid shifts in cultural practices or economies to adapt to prior changes in climate.
- If there are actions managers, industry, and communities might take to help mitigate the exposure of species or key ecosystem linkages to climate change.
- If there actions that managers, industry, and communities might be able to take to mitigate other effects of compounding environmental stressors that might help offset the effects of climate change.

5) Recommendations for further research and potential actions or strategies for adaptation

Finally, we asked expert teams-- based on what they have learned in earlier phases-- to make recommendations to the leadership of the three sponsoring entities (ABSI LCC, Alaska Climate Science Center, and AOOS) on key next steps for research as well as potential adaptation measures that would currently be feasible. We asked them to consider:

- What additional key data or information was needed that would be vital for improving identification and understanding of climate impacts.
- If there were specific studies, inquiries, syntheses or collaborations that should be launched to improve the ability of managers and stakeholders to understand and address climate change.
- If there were 'no regrets' strategies that are feasible for managers, industry, communities to take that could address vulnerabilities identified by the group.

Chapter outlines were developed by the five teams over several months, and each team was assigned a member of the core team to ensure there was coordination between teams. Prior to completion, these chapter outlines were also shared be each team at a full meeting of the expert team. The focus of that meeting was to identify potential commonalities is recommendations for important research topics being made by each of the teams. These resulting recommendations are the key outcome of the overall assessment process and understanding their nature and scope helped the core team design a process to integrate and prioritize them (see chapter 7). Finally, the initial conclusions by the five chapter teams were also used to design a community stakeholder session with residents in the ABSI region's largest community of Unalaska/Dutch Harbor (see box 1.1).

Discussion

Given the relatively rapid nature of this assessment process (~12 months) as well as the scope and complexity of the topic we knew the experts would not be able to complete a fully integrated assessment of climate change impacts. From the first workshops that launched the project, we regularly reminded the expert team that this coarse-filter assessment was a first step. We knew that given the time and financial constraints of the project (<$100,000) we would not be able to fund salary time necessary to complete the development of exhaustive chapters. Rather, we set the expectation that this effort would identify *selected* key points of vulnerability that would help narrow the focus of near-term investments and collaborations related to climate change between the ABSI LCC, the Alaska Climate Science Center, and AOOS as we attempt to serve managers and stakeholders in this region.

We acknowledge that the process of vulnerability assessment varies considerably, and as a result we allowed for variation in the application of the Glick et al. framework for vulnerability assessments. In many cases this was necessary due to the variation in the degree in applicability to each of the Glick et al. five steps for assessment, the information available for synthesis, and the degree of detail that each team chose to consider as they developed their individual chapters. For our coarse-filter approach to be able to consider species and sociocultural affects, this more open process was necessary and resulted in some differences in the depth that topics were addressed in each chapter. Similarly, though the geographic focus area provided to our expert teams was the boundary of the ABSI LCC, some issues were better described by allowing for consideration of communities or habitats adjacent to this region.

Limitations on the availability of information for understanding climate effects on vegetation in the region prevented the authors from completing a full vulnerability assessment chapter for terrestrial vegetation. Instead the authors focused on what information was available about vegetation in the region and how that might relate to climate change. Their short synthesis is provided at the end of this report as Appendix A.

Throughout the development of this assessment we made deliberate efforts to promote sharing of perspectives between our five teams with the intent of integrating scientific perspectives. This approach was taken with the aim of fostering interdisciplinary learning between the five teams as well as identifying shared information needs and mitigation strategies with benefits to multiple species and ecosystem services. We are hopeful that the collaborations between diverse groups of scientists may be continue and be an additional important outcome of this work.

Our intention is that the results of this assessment might guide the future actions of the three ABCVA partner organizations, and we hope it may be of use (in terms of both process and results) to other organizations that manage resources or that fund, plan, or conduct research in the ABSI region. We also hope that this body of work may help provide an understanding of the implications of climate change for managers, industry and communities. The funding partners and contributors to this project came together with the common vision that collectively we can work together to address climate change vulnerabilities in the Aleutian Islands and Bering Sea region. We hope this assessment can be a first step toward developing the information and data needed to inform coordinated action toward adaptation.

This Volume

Here we present four stand-alone chapters authored by the expert teams, each attempting to highlight what is known about vulnerabilities for key resources and

ecosystem services in the region in relation to projected changes in climate. As authors developed chapter content we asked them to think about research items that would help managers understand those vulnerabilities as well as potential management strategies that might help mitigate impacts from climate change. It should be noted that the management strategies presented in some chapters were not intended to be prioritized, and are included *only* for informational purposes to show the types of potential action that could be taken to address climate impacts.)

A concluding chapter (Chapter 7) describes how research items identified by the chapter teams were then prioritized using a Structured Decision Making process (Gregory and Keeney 2002, Conroy and Peterson 2013). **A list of prioritized research topics is presented in Chapter 7, Table 2.** We chose this method to integrate the perspectives of experts relative to important climate change information needs within the region. Our intent was that this rapid workshop process would take the place of a traditional written synthesis of individual chapter conclusions—while still yielding the key information (35 prioritized research topics) needed by our three organizations.

Acknowledgements

It is very noteworthy that other than the four project coordinators and one data analyst, *all* contributors generously volunteered their in-kind time to the development of this assessment. Over a period of just over a year, this added up to hundreds of person-hours, the majority of which came from senior scientists in their fields. The leadership and staff from ABSI LCC, AOOS, and the Alaska Climate Science Center are extremely grateful to the full group of researchers listed in Table 1. It is our hope that their contributions here, as well as their interest in coming together as an integrated group of scientists, can inspire further interdisciplinary collaboration on the science needs of managers and stakeholders attempting to address large scale threats like climate change.

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Table 1. The ABCVA Expert Teams

Matt Carlson	Alaska Natural Heritage Program	Terrestrial Vegetation
Lee Cooper	University of Maryland	Fish/shellfish
Debbie Corbett	former USFWS	Human Dimensions
Carol Fairfield	BOEM - Alaska OCS Region,	Marine Mammals
Verena Gill	FWS - Marine Mammal Management	Marine Mammals
Diane Hanson	University of Alaska Anchorage	Human Dimensions
Henry Huntington	Pew Charitable Trusts	Human Dimensions
Will Koeppen	Axiom Consulting Inc.	Seabirds
Gordon Kruse	University of Alaska, Fairbanks	Fish/shellfish
Kathy Kuletz	FWS - Migratory Bird Management	Seabirds
Sean Mack	Bureau of Indian Affairs	Human Dimensions
Liza Mack	University of Alaska, Fairbanks	Human Dimensions
Jim McCracken	USFWS - Marine Mammal Management	Marine Mammals
Nicole Misarti	University of Alaska, Fairbanks	Human Dimensions
Franz Mueter	University of Alaska, Fairbanks	Fish/shellfish
Phil Mundy	NOAA - Alaska Fisheries Science	Fish/shellfish

	Center	
Liliana Naves	ADF&G Subsistence	Human Dimensions
Karen Pletnikoff	Aleutian and Pribilof Islands Association	Human Dimensions
Lori Polasek	Alaska SeaLife Center & University of Alaska	Marine Mammals
Julie Raymond-Yakobian	Kawerak	Human Dimensions
Heather Renner	FWS - Alaska Maritime National Wildlife Refuge	Seabirds
Suresh Sethi	FWS - Fisheries and Ecological Services	Fish/shellfish
Chris Siddon	ADF&G - Division of Commercial Fisheries	Fish/shellfish
Mike Sigler	NOAA- AFSC	Fish/shellfish
Melanie Smith	Audubon Alaska	Seabirds
Andrew Trites	University of British Columbia	Marine Mammals
Jeff Williams	FWS - Alaska Maritime National Wildlife Refuge	Seabirds

Box1.1: Beginning a Conversation on Climate with the Community of Unalaska
Aaron Poe, Ellen Tyler, Chris Beck, and Meghan Holtan




The Aleutians divide the Bering Sea from the rest of the North Pacific, and together with a handful of other islands in the region, are home to nine island communities. These communities are some of the most isolated in the United States and their residents depend on the region's highly productive marine system. Changing weather conditions and warmer ocean waters threaten the viability of traditional harvest practices that Alaska Native tribes of this region have used for generations. They also threaten the commercial fishing industry that is vital to the region's economy and which accounts for 50 percent of the total annual U.S. seafood harvest.

As we brought together ideas from assessment team of 30 scientists and managers, we knew that we wanted to find ways to share some of their initial thoughts about important climate effects with the people who live, work and play in the region. Unalaska and Dutch Harbor (hereafter, Unalaska) together make up the largest community within the region. With its 4,500 residents, Unalaska is a hub for the other communities in the Aleutians, the largest fishing port in the U.S. and is also a key port supporting international trade between North America and Asia. We were hopeful that by sharing some our team's initial conclusions we would have the opportunity to receive feedback to help guide our work. Beyond sharing our early efforts, we also wanted to hear what residents of this hub community were seeing and hearing about in their region that they attribute to climate change.

Our Approach:

Given the expense of reaching a remote community like Unalaska we wanted to take every opportunity to engage people about our work. Though our initial focus of the project had been developing a single 'town hall' type session—we wanted to use this opportunity to connect with the community in other ways during our visit. During a three-day period we met with leaders from the local government, including the Port of Dutch Harbor and the Tribal Council, business leaders, a civic group, and a group of elders. We also conducted three press engagements including a newspaper story prior to our arrival in Unalaska, an interview with the local public radio affiliate, and guesting on a live morning radio show. We were also able to work with the schools to bring an environmental educator in to present a science curriculum that she had developed in part based on the work of our assessment team.

At the outset we knew we needed local expertise to help us plan, advertise, and execute our community engagement efforts. Working with the Qawalangin Tribe of Unalaska as well as a local biologist from the Alaska Department of Fish and Game we were able to secure a venue for our town hall session at the Museum of The Aleutians. This venue was deliberately chosen to reflect our intent of knowledge exchange. Our local organizers donated their time and were excellent ambassadors for the project driving turnout for our town hall session and setting up additional meetings for us to speak with local leaders about our work.

To help us design and facilitate the town hall session, we engaged the services of an Anchorage-based community planning firm called Agnew::Beck that has experience working with communities in the region. They helped us design a session that could be free-flowing, where residents had the opportunity to hear each other's perspectives as well as learn from us *and* provide us constructive feedback on our work. We used audience response technology as a tool to live poll the audience during the session. This tool allowed us to record responses systematically and shares those responses in the form of bar chart summaries with the audience in real-time.

Using this approach we presented three different sections of our work looking at physical, biological, and human components to climate change. Short presentations were offered at the outset of each section to orient audience members to expected changes in climate and the implications of those changes based on our team of experts. Following each presentation we asked the audience to react to a series of questions. We then presented the polling results of their responses back to them to elicit further qualitative insights through discussion.

We asked questions about long term changes in weather observed in the region and asked if the projections being made by our expert team about climate generally reflected their observations. We shared information about the species of fish and wildlife that our experts thought might be most affected by climate changes and asked for local insights about changes they may have observed in those species. We also asked them to prioritize concerns they had relative to climate change and about implications for their community and the natural and cultural resources in their region. Finally we asked them to reflect on the types of information the community most needs to better understand and adapt to climate change.

All questions were categorical along a gradient of response. For example when asked "to what extent have you noticed climate change effects on infrastructure?" response options ranged from: 1) I have definitely noticed this change; 2) I have noticed this to some extent; 3)I've heard others talking about this but haven't noticed it myself; 4) I have not noticed this change; and 5) I don't know. Following question the responses were projected for the audience to see and our facilitator queried the audience with follow up questions about their results asking willing individuals to offer up there specific insights about changes they had seen. During these follow discussions our facilitator made considerable effort to draw out perspectives from individuals who had differing opinions from the rest of the audience or who offered a perspective differing from the conclusions of our expert team.

Results & Discussion:

During our two hour town hall we covered 27 polling questions many of which were led to rich follow up discussion. The event was well attended with about 40 individuals coming out to the session which at the outset left standing room only for the room we had selected. It was also videotaped and broadcasted as a feature presentation a few days later by the local public television station.

We heard about a number of changes residents already see that they attribute to climate change. They ranked increases in air and ocean temperatures as well as increased storminess/shifting wind patterns as the biggest changes they have observed. They identified crab species, halibut and pollock as species that they have observed changes that they attribute to potential changes in climate. They ranked changes most commonly observed as: shifts in locations used by these species; an overall decrease in abundance; and a change in timing of when they could be reliably harvested. The audience ranked observed changes in whales and sea lions as most obvious among marine mammals and these changes were most commonly described as a shift in locations used by these species.

Relative to human communities they identified decreases in commercial and subsistence species as being of greatest concern. They also identified increased costs and safety concerns relative to storminess as a challenge presented by climate that makes it more difficult to harvest target species. They identified threats to infrastructure, and the spread of environmental pathogens like paralytic shellfish poisoning, or "PSP", as water temperature increases. Residents also expressed concerns about climate change interacting with possible impacts from the complex and sophisticated fishing industry that is so vital to their region's economy.

Lessons Learned:

From inception, our team realized that a well-attended public session on a somewhat nebulous topic like climate change, that wasn't connected to some specific, proposed change in management, would be a challenge. We also realized that the majority of our assessment team, though very experienced in conducting science in the region, were not themselves residents and this could lead to challenges for advertising the planned session in an effective and engaging way for Unalaska residents. Having the support of local, well-connected project ambassadors was essential for planning a relevant and meaningful session. It was also critical for generating turnout to the town hall session as well as connecting with local leaders about the project.

The topic of climate change is still controversial. We knew we didn't want that to overshadow or derail a productive exchange of information. We also recognized that this is a challenging topic to present with clarity and authority while still conveying the uncertainty inherent in projections about the future climate changes. Being able to bring in facilitation experts who have worked in the region to help our assessment team to develop the town hall presentation content was extremely valuable. Similarly, the use of audience response technology proved very useful for showing the range of perspectives in the room. Further it allowed us to collect complete and anonymous reactions to the material that we presented to see how the audience was responding while allowing our facilitator to probe more deeply about those responses.

People in this region are acutely aware of change, impacts and threats from climate change. Budget and logistical limitations prevented us from taking this project to multiple communities in the region during the timeframe of this assessment but the feedback and perspectives shared underscore the importance for more of this type of structured, two-way information exchange. It is our hope this initial effort in Unalaska was an opportunity to improve our approach as well as establish some relationships within the region that will help us make more of this type of work happen in the future.

Chapter 2: Climate Projections for the Aleutians and Bering Sea

Jeremy Littell, Aaron Poe, Nick Bond

Introduction

The results from global climate model simulations have been evaluated (Walsh *et al*. 2008, Overland *et al*. 2011) and downscaled (Hermann *et al*. 2013, SNAP 2014) to project future climatic and environmental conditions for the region of the Aleutian Islands and Bering Sea. Results from two of these efforts can be explored using online resources from the Scenarios Network for Alaska & Arctic Planning (SNAP, https://www.snap.uaf.edu/tools-and-data/all-analysis-tools) and the AOOS data portal (http://data.aoos.org/). These two recent downscaling efforts became the foundation for this vulnerability assessment and the content in this chapter was shared with our Expert Team at the outset of this project.

Before delving into the expected changes in the atmosphere-ocean climate of the Aleutian Islands/Bering Sea summarized below, it bears noting two important considerations. First, this region experiences considerable variability on interannual to decadal time scales, and these variations have dominated the systematic changes to date (e.g., Wendler *et al*. 2013). Second, while climate models agree that air temperature will increase, there is less agreement on projected precipitation rates, changes in seasonal storminess, and changes in wind and ocean current speeds and direction. For each set of modeled atmospheric, oceanic and ice projections, the strength of across-model agreement is noted and interannual and decadal fluctuations will continue to be prominent, possibly exceeding the magnitude of long-term trends for at least a couple of decades into the future. Moreover, multi-year fluctuations in the climate cannot yet be predicted in advance, and so it will be difficult at best to determine when the climate has entered any new state.

Climate Scenarios

Climate scenarios are plausible future trajectories of elements of the climate system – temperature, precipitation, wind, sea surface temperature, sea ice, etc.—given our knowledge of the climate system and certain assumptions about forcings on that system (e.g., greenhouse gas emissions). Climate scenarios are projections – not predictions and not forecasts – of the climate that may unfold in the future given the climate system information incorporated in a climate model. Many of the useful climate scenarios are derived from computer models, but it is worth noting that not all scenarios are derived exclusively from global climate models. Climate science is sufficiently well developed that modeling can constrain estimates of future climate decades into the future to plausible bounds – what the climate might become, given several variables including initial conditions of the climate system, the forcings on that system, and the climate system's internal dynamics. But they are not as well developed for near-term forecasting, such as weather forecasts or other near-term predictions, and so they are called projections. Fortunately, climate models' strength is in their responsiveness to forcings, and they do a reasonable job of projecting average climate at global and regional scales far into the future.

Climate scenarios may be as simple as one variable averaged over several climate models and across several decades, such as: “the temperature in the Aleutian Bering Sea Island region will increase approximately 2 to 2.5 degrees Fahrenheit on average by the period 2040 to 2049, relative to a baseline of 1971-2000”. A more complicated climate scenario might be the physically consistent temperature, precipitation, wind fields, sea surface temperature, sea ice, and sea level pressure – essentially the basics of the climate system in the region – in an annual time series from 2014 until 2100.

Whatever the case, climate scenarios are useful for describing a future climate, its possible impacts, and the vulnerability of existing resources and systems. One use of climate scenarios is in “scenario planning”, in which a few plausible scenarios of future climate, perhaps derived from global climate models and other information, are compared for their likely impacts on systems or resources. The impacts common to all scenarios are more likely to be robust and are things that participants may lean towards planning for while impacts that appear in only one or a few scenarios may or may not factor into planning decisions based on a community’s tolerance for risk.

Uncertainty in Climate Scenarios

The climate scenarios used in this assessment come from models, and are therefore subject to some uncertainty because models cannot simulate all aspects of the climate system, and in particular, there are interactions (say between atmospheric aerosols and clouds) that are not yet well understood by science and these "left out" parts sometimes result in model errors. There are three main sources of uncertainty in climate scenarios: intrinsic climate variability, climate model error, and greenhouse gas emissions forcing (e.g., Hawkins and Sutton 2009)[1].

Intrinsic variability of the climate system (particularly on the order of years to decades) is very complicated to model, and most climate models do a reasonable job of projecting multi-decadal trends due to forcing but do not do a very good job of predicting the year-to-year and decade-to-decade variations that occur naturally as part of the climate system. For thirty or so years into the future, this uncertainty is the largest. After that, and until about 60 years into the future, the biggest source of uncertainty is model error—or the differences in projections among climate models due to difference in their construction (the things they leave out or including how sensitive they are to greenhouse gas forcing). Finally, later in the 21st century, the uncertainty about the quantities of greenhouse gasses that will be emitted between now and the end of the century is the dominant source of uncertainty, and uncertainty due to model error and intrinsic variability are small compared to emissions uncertainty.

The climate scenarios chosen for a workshop or planning exercise therefore are guided somewhat by the time frame required by the decision makers or participants. There is no need to worry about comparing 25 different models if most of the important time line is in the next 30 years – model variability is small compared to decadal climate variability in that time frame, and a middle-of-the-road mean scenario and a few bracketing scenarios may suffice (Littell et al. 2011)[2]. Similarly, the emissions in the atmosphere at present and likely to be in the atmosphere in the next 30 years are largely a function of choices made now, so emissions scenarios don't begin to diverge radically until the 2050s or even later. Comparing 4 emissions scenarios for the period 2040 to 2060 isn't all that useful because we are certainly not headed for lower emissions scenarios and the higher ones don't differ that much on their impacts on global temperature until after the 2060s. So choosing climate models and emissions scenarios needs to be done carefully (e.g., Snover et al. 2013), but it is fortunately considerably simpler than modeling climate.

Climate Downscaling

Downscaling is the process of taking the resolution of climate projections from global climate models (often pixels about 1 to 2 degrees latitude by 1 to 2 degrees longitude, or about 90 to 180miles on a side) and making them more specific to much more local resolution (from half a mile to 25 miles is typical). There are (at least) two general ways to do this. The first approach is to develop statistical relationships between (1) the local, historical climate interpolated over the land surface between weather stations and (2) the historical climate estimated by the global

[1] Ed Hawkins and Rowan Sutton, 2009: The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bull. Amer. Meteor. Soc.*, **90**, 1095–1107

[2] Jeremy S. Littell, Donald McKenzie, Becky K. Kerns, Samuel Cushman, and Charles G. Shaw 2011. Managing uncertainty in climate-driven ecological models to inform adaptation to climate change. Ecosphere 2:art102. http://dx.doi.org/10.1890/ES11-00114.1

climate model at coarser scale. In other words, each large-scale cell from the climate model has multiple relationships with the smaller cells within its boundaries for which we have estimates of historical climate. These relationships are then used to "downscale" the future changes projected by the climate model to more local scales.

The second approach is called regional climate modeling or dynamical downscaling. This approach involves using a global climate model to define the coarse conditions of the climate and then using a weather forecasting model to determine what those "boundary" conditions would mean for more local scales.

Downscaling methods have different advantages and disadvantages. Statistical downscaling is relatively fast to do on a computer, but it depends on good historical climate data (which is not always available in sparsely populated areas or over the ocean) and it assumes that the statistical relationships in the historical period will hold in the future. Dynamical downscaling is much more computationally intensive and therefore takes more time and money to produce an equivalent set of projections, but it also allows for more local physical information to guide the downscaling of the coarse climate from the climate model and it necessarily requires all of its outputs to be physically consistent – that is, the elements of the climate depend on each other in realistic ways and are modeled as such.

As a note of caution, downscaling is often useful, but it also can create a false sense of realistic detail (Snover et al. 2013)– if there are few good climate stations in a region, as there are for the ABSI LCC, statistical downscaling in particular will necessarily involve more assumptions about how local conditions (including topography, vegetation, land use, etc.) affect the climate at fine scales (say, in kilometers).

Example climate projections for the ABSI region

For this vulnerability assessment, we used several datasets of historical climate and future projected climate to develop future scenarios of climate. Below, we present examples of projections for climate variables that were used to introduce core team members to thinking about implications for resource and service vulnerabilities. Appendix A. lists some available scenarios and their attendant emissions, climate model, variables and sources.

Scenarios Network for Alaska and Arctic Planning (SNAP) has downscaled five global climate models that perform well in Alaska and developed localized projections (SNAP 2014)[3]. Further information and tools that serve data on climate projections are available online at the SNAP website [available at: www.snap.uaf.edu]. Our examples help showcase some of the functionality of those tools. Figures 2 and 3 show an example community temperature and precipitation projection for the Adak station in the ABSI LCC region. Information for each community is based on the closest 2 km by 2 km pixel from SNAP's datasets. The charts show historical PRISM climatology data and downscaled outputs averaged from five climate models.

[3] SNAP (Scenarios Network for Alaska and Arctic Planning, University of Alaska). 2014. Projected Monthly Temperature - 1 km CMIP3/AR4. Accessed 12/2014 from http://ckan.snap.uaf.edu/dataset/projected-monthly-temperature-1-km-cmip3-ar4.

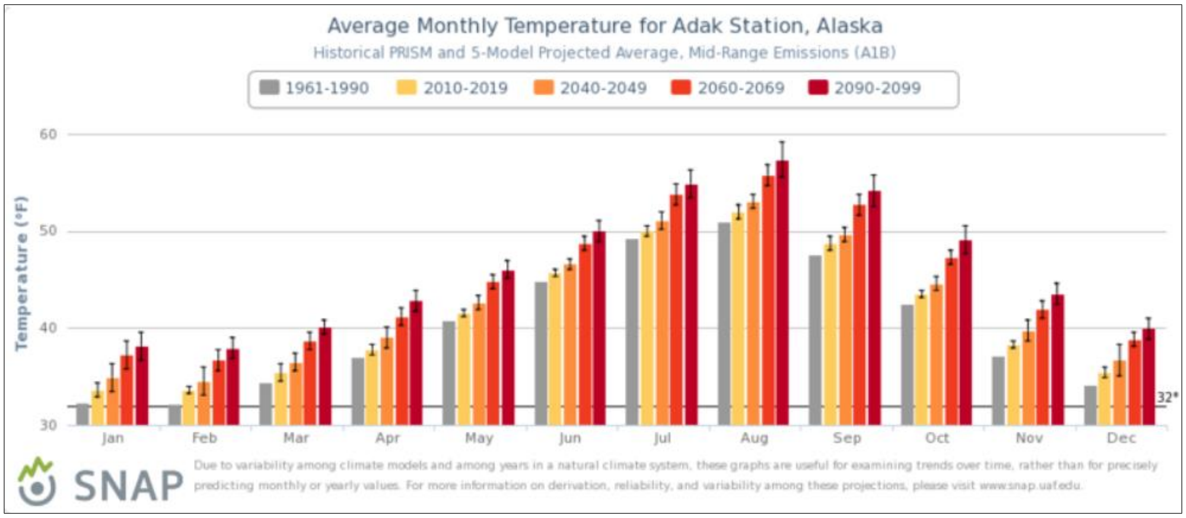

Figure 2. Decadal average monthly temperature (ºF) for Adak, one of 6 communities in the ABSI LCC region for which projections are available. Historical (gray) compared to 4 future decades. Bar heights for future projections are 5-model means; error bars represent the range of model projections. Available online at: http://www.snap.uaf.edu/charts.php

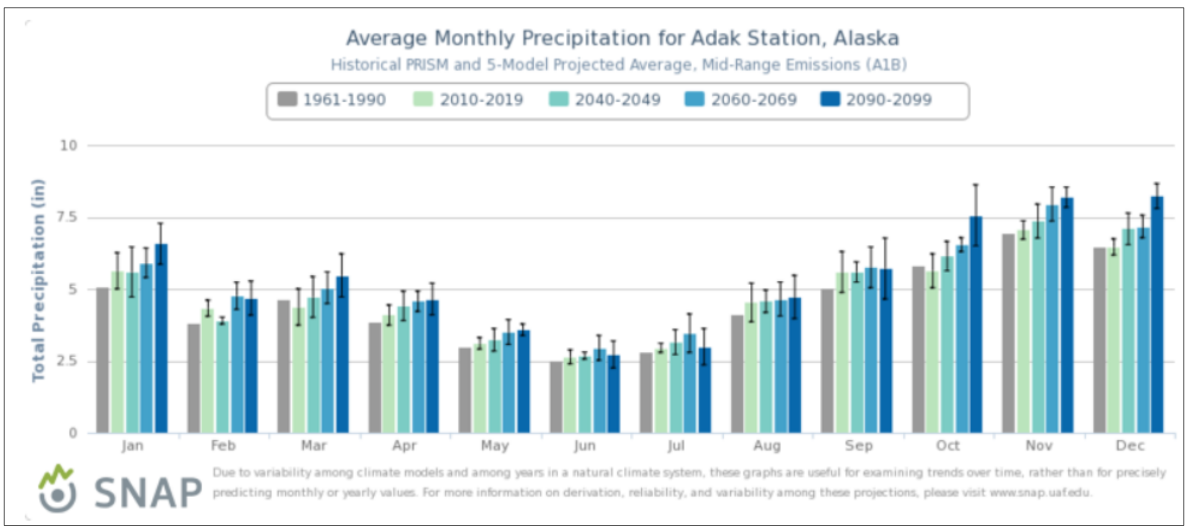

Figure 3. Decadal averaged monthly precipitation for Adak, one of 6 communities in the ABSI LCC region for which projects are available. Historical (gray) compared to 4 future decades. Bar heights for future projections are 5-model means; error bars represent the range of model projections. Available online at: http://www.snap.uaf.edu/charts.php

Temperature increases in all months and all decades for each of the region's six communities (Table 1), with increases larger after 2040, and varying with location and season. Precipitation generally increases, though the magnitude of the increase varies with time and place. It is worth noting that often, the decadal averages of GCM projected precipitation increases are generally within the range of historically experienced years, but this approach to downscaling does not reflect extremes. It also remains to be seen whether more dynamically consistent approaches to climate modeling (e.g., regional climate modeling / dynamical downscaling) produce different results. There is important sub-regional variability in the projected temperatures for these communities, reflecting different response possibly driven by the north-south gradient and/or relationship to sea ice.

Table 1. Scenario-average (A1B) projected temperature changes (°F) for the decade 2040-2049 by season for six ABSI-LCC communities. These estimates are made from the community charts generated online at: http://www.snap.uaf.edu/charts.php

Community	December January February	March April May	June July August	September October November
Savoonga	8.0	4.0	1.5	2.5
Shemya	2.5*	2.0	2.0	2.5
Adak	2.5	2.0	2.0	2.5
Saint George	5	3.5	2.5	2.5
Unalaska	3*	2.5	2.0	2.5
Nikolski	3	2.5	2.0	2.0

* indicates two or more months in the season increase from below freezing to above freezing.

In addition new projections associated with the new generation of global climate models (CMIP5) are also available for a number of coastal/marine grid cells in the ABSI region from SNAP. These include the ability to look at projected changes in extreme events associated with wind and temperature. Figures 4 – 5 are example summaries that can be generated online at: http://spark.rstudio.com/uafsnap/temp_wind_events/.

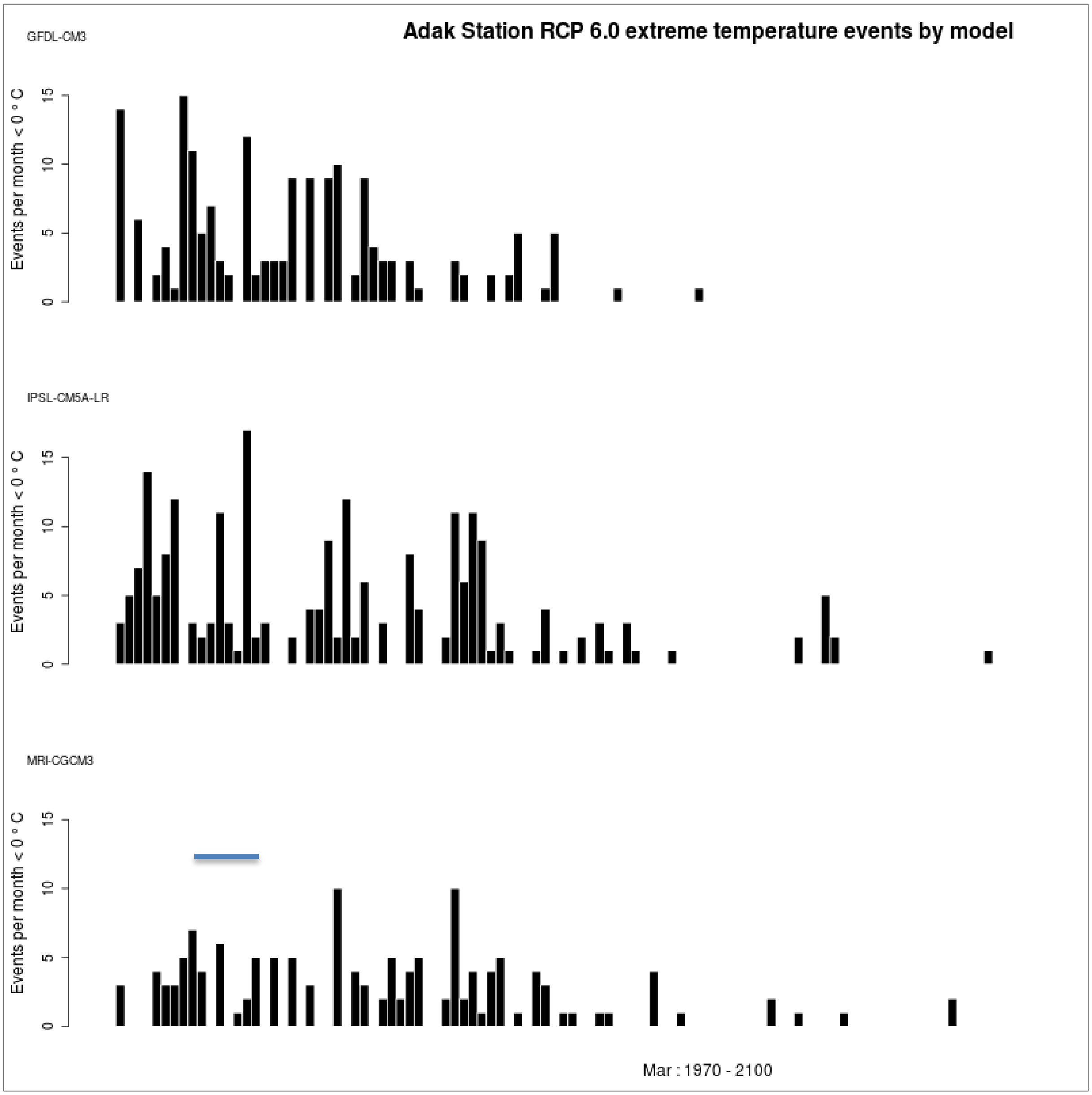

Figure 4. Changes in number of March days below freezing at Adak, projected using three different global climate models for the period 1970 – 2100. Developed using M. Leonawicz's shiny app online at: http://spark.rstudio.com/uafsnap/temp_wind_events/

A plausible scenario on Adak is that the period 2001 – 2030 is *possibly* different than 1971-2000 in the number of events <0 °C per month in March, but the variability year-to-year and across models makes that a tenuous conclusion. What is clear about the period from 2031-2060 is that the number of events <0 °C declines substantially.

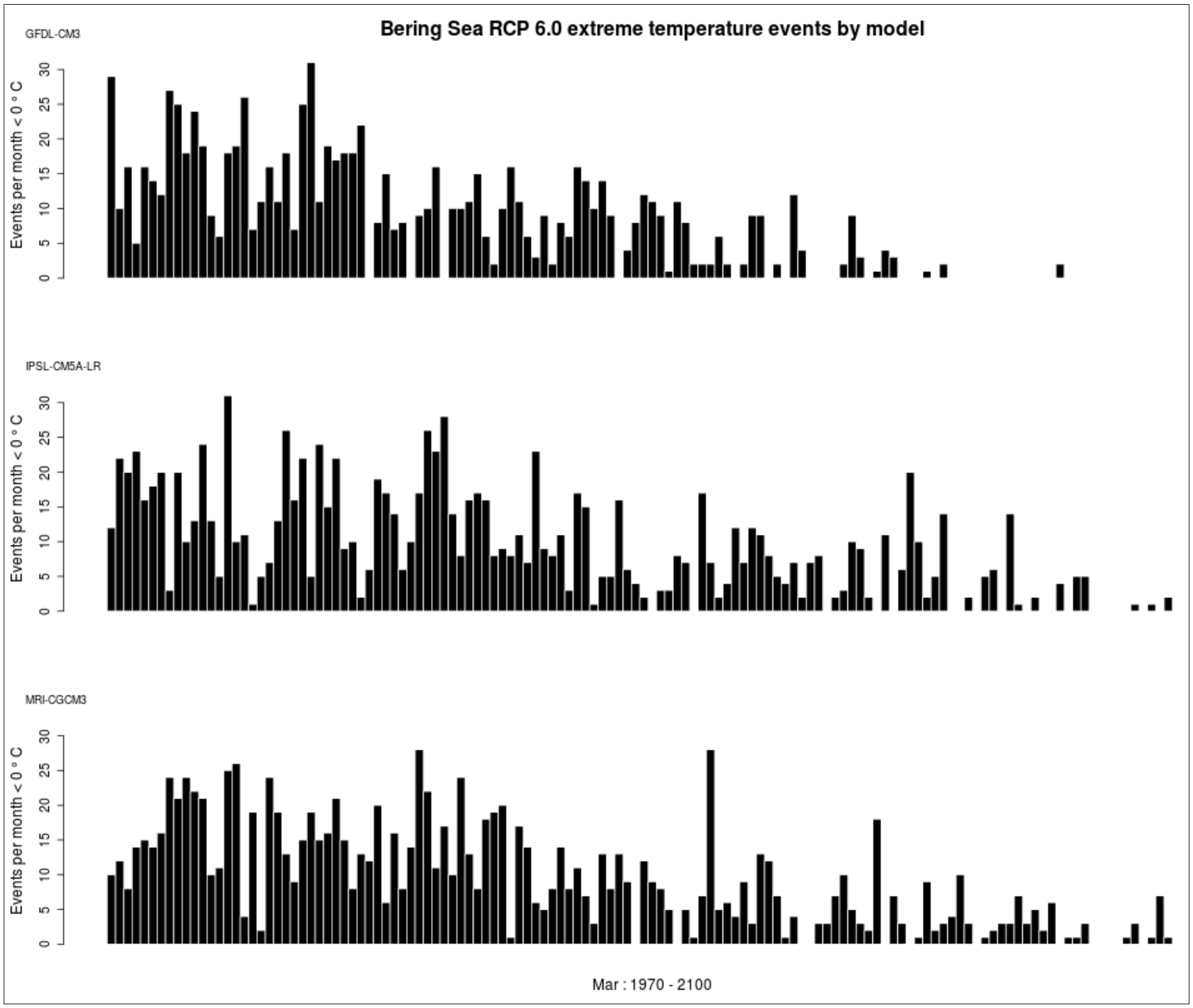

Figure 5. Frequency of extreme temperature events for a marine grid cell within the Bering Sea between 1970 and 2100. Developed using M. Leonawicz's shiny app online at: http://spark.rstudio.com/uafsnap/temp_wind_events/

In the Bering Sea, on the other hand, the trend is evident though the near-complete absence of days <0 °C observed at Adak is not observed. Note the differences among models – GFDL shows a near complete loss of days <0 °C in the late 21st century, whereas IPSL and CGCM show decreases, but still some days colder than that threshold. In addition to extreme temperature events this tool also allows users to assess frequency of extreme wind events.

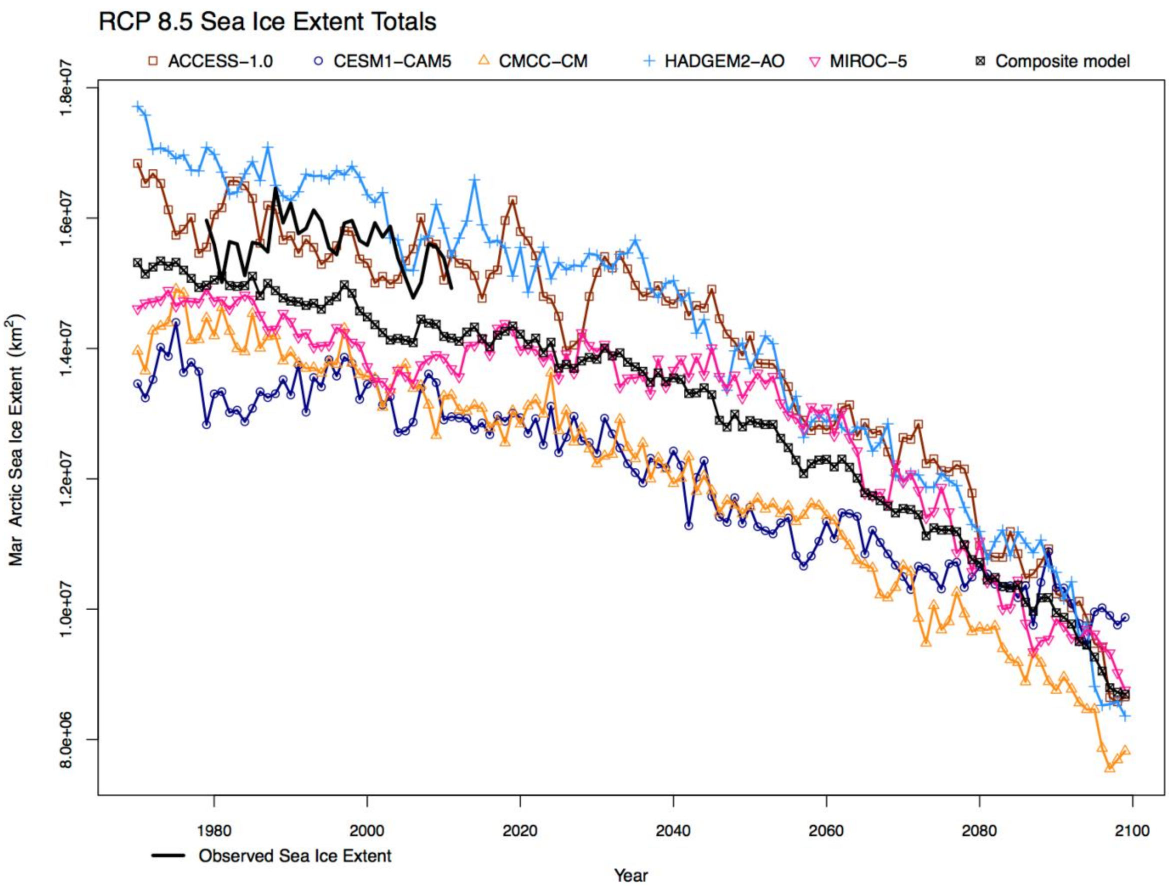

Figure 6. Pan-arctic sea ice extent from observations (black line with no symbols), 5 different GCMs, and the composite of 5 models for March, 1970-2100. Developed using M. Leonawicz's shiny app online at: http://blog.snap.uaf.edu/2013/05/20/r-shiny-web-app-sea-ice/

For sea ice scenarios, a couple of important points emerge from Figure 6. First, three of the five models, and the five-model-mean, under predict sea ice extent during the observational record from 1980 to 2010. This may indicate those models fail to simulate some important aspect of the system, and so they have a bias toward lower than observed projections. On the other hand, most of the models converge in the future, and no model projects increasing sea ice extent. So the plausible scenario is a decrease, but a key aspect would be how it affects the ABSI region – these are pan-Arctic, and it would be useful to track single regions.

Projections for climate-related biophysical variables

Projections of the Bering Sea's response to climate forcing by Hermann et al. (2013)[4] were also made available to support this vulnerability assessment. This team used a dynamical approach to extract the emergent properties of a coupled physical/biological hindcast from the Bering Sea for years 1970–2009. This period includes multiple episodes of warming and cooling (including

[4] Hermann, A. J., G. A. Gibson, N. A. Bond, E. N. Curchitser, K. Hedstrom, W. Cheng, M. Wang, P. Stabeno, L. Eisner and K. D. Ceiciel. 2013. A multivariate analysis of observed and modeled biophysical variability on the Bering Sea shelf: Multidecadal hindcasts (1970-2009) and forecasts (2010-2040). Deep Sea Research II 94:121-139.

the recent cooling of 2005–2009), and is compared with multi-decadal regional projections based on IPCC global climate model simulations for 2010–2040. Further variables were derived from ROMS Bering 10k physical oceanography and coupled biological model. These efforts produced projections for the following biological and physical variables:

Biological
Ice algae
Small plus large phytoplankton (depth average)
Microzooplankton (depth average)
Small copepods (depth average)
Neocalanus (depth average)
Euphausiids (depth average)
Benthic detritus
Benthic infauna

Physical
Surface temperature
Bottom temperature
Surface salinity
Ice cover
Mixed layer depth
Vertical MIXING (depth average)
Nitrate+ammonium (depth average)

Projections for these variables have been summarized spatially using gridded data and examples include Figures 7 and 8. Given the uncertainties associated with these projections they are presented under different coupled climate models. The ABCVA team is currently working with these projected datasets to develop a tool that will support analysis by the expert team. The current design concept is a *virtual sensor* that will allow spatial sampling of the gridded data from these projections. Mapped depictions of change for these variables similar to figures 7 and 8 can also be made available.

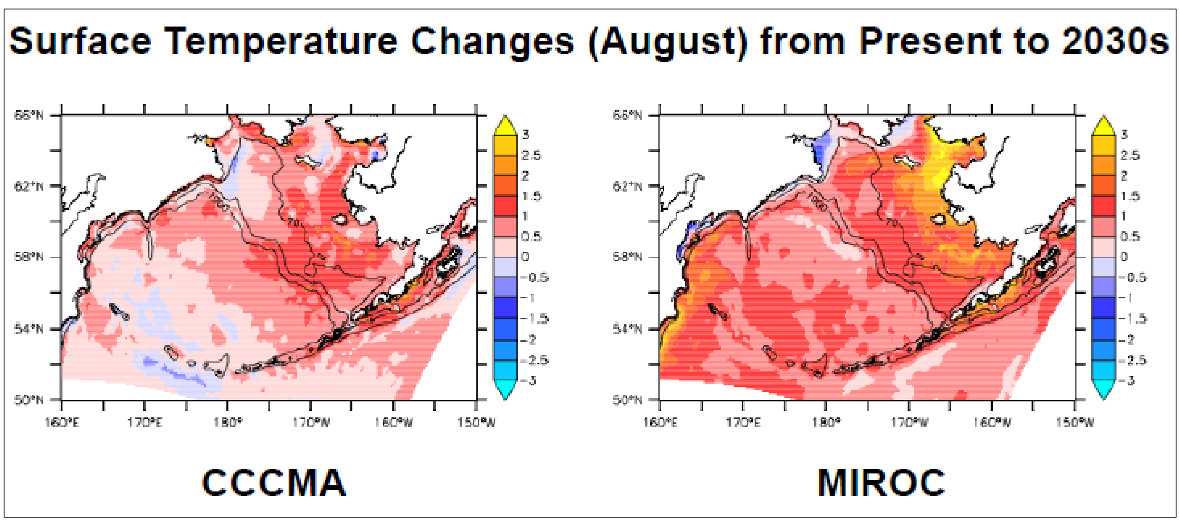

Figure 7. Sea surface temperatures (°C) from the present to the 2030s for the month of August as projected by two coupled models CCCMA and MIROC.

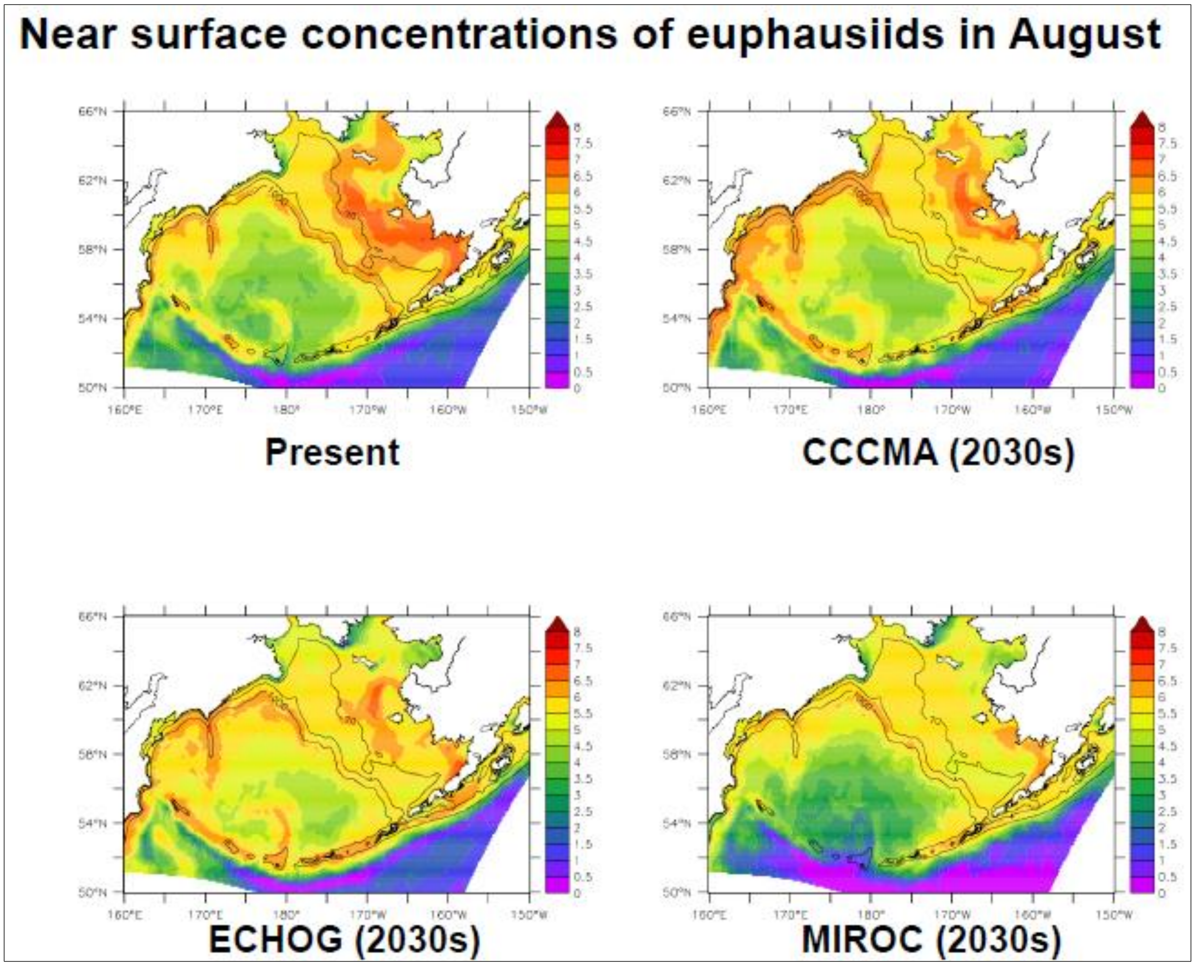

Figure 8. Near surface concentrations of euphausiids during the month of August (mg C m^{-3}) from the present to the 2030s for the month of August as projected by three coupled models CCCMA, MIROC, and ECHOG.

Appendix A. Library of available scenarios in the ABSI region (as of December 2013)

Emissions	Climate Model	Variables	Scenario(s)	Source
A1B	CGCM3.1-t47	Temperature, precipitation, pressure, runoff, wind, radiation, humidity	+1.0 to +1.5C SST by 2035	Bond / Hermann
A1B, A2	CGCM3.1-t47	Temperature, Precipitation	Depends on community	SNAP
A1B, A2	Echam 5	Temperature, Precipitation	Depends on community	SNAP
A1B, A2	GFDL 2.1	Temperature, Precipitation	Depends on community	SNAP
A1B, A2	hadCM3	Temperature, Precipitation	Depends on community	SNAP
A1B, A2	Miroc3.2 medres	Temperature, Precipitation	Depends on community	SNAP
RCP 6.0, RCP 8.5	GFDL CM3	Temperature, wind		SNAP[1]
RCP 6.0, RCP 8.5	IPSL CM5A LR	Temperature, wind		SNAP[1]
RCP 6.0, RCP 8.5	MRI CGCM3	Temperature, wind		SNAP[1]
RCP 8.5	CMCC CM	Sea ice extent		SNAP[2]
RCP 8.5	HADGEM2 AO	Sea ice extent		SNAP[2]
RCP 8.5	MIROC5	Sea ice extent		SNAP[2]
RCP 8.5	CESM1 CAM5	Sea ice extent		SNAP[2]
RCP 8.5	ACCESS 1.0	Sea ice extent		SNAP[2]

[1] Visuals M. Leonawicz via ShinyApp at: http://blog.snap.uaf.edu/2013/05/20/r-shiny-web-app-extreme-events/
[2] Visuals via ShinyApp at: http://blog.snap.uaf.edu/2013/05/20/r-shiny-web-app-sea-ice/

Chapter 3: Aleutian and Bering Climate Vulnerability Assessment-- Fish and shellfish

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Introduction to the Physical Environment

The Aleutian Islands and the eastern Bering Sea region comprises a variety of habitats that include predominantly sandy (Bering Sea) or rocky (Aleutians) coastal areas, a broad continental shelf with sandy and muddy sediments, and a continental slope with a mixture of soft sediments and hard substrate, including deep-water corals. Both the Aleutian Islands and the eastern Bering Sea shelf are highly dynamic environments with longstanding biophysical relationships pertaining to, or resulting from, the present climate -- which means that biophysical mechanisms, and the ecological models based on them, are subject to change.

Temperature, turbulence and transport are some of the mechanisms through which the physical environment influences biological processes (Stabeno *et al*., 2014). Within the larger Aleutian and Bering Sea region, changes in climate and other related elements of these ecosystems are likely to have stronger and more immediate impacts to fish in some areas more than others because: (1) important physical drivers may undergo pronounced directional changes, such as temperature in the nearshore and ice conditions on the middle shelf; (2) certain areas provide critical habitat for fish or shellfish and could act as bottlenecks in the life history of species that are more sensitive to climate variability; or (3) the intensity or spatial distribution of (predation by) higher trophic level animals, including marine mammals, humans and seabirds may alter survival rates.

Introduction to the Species at Risk

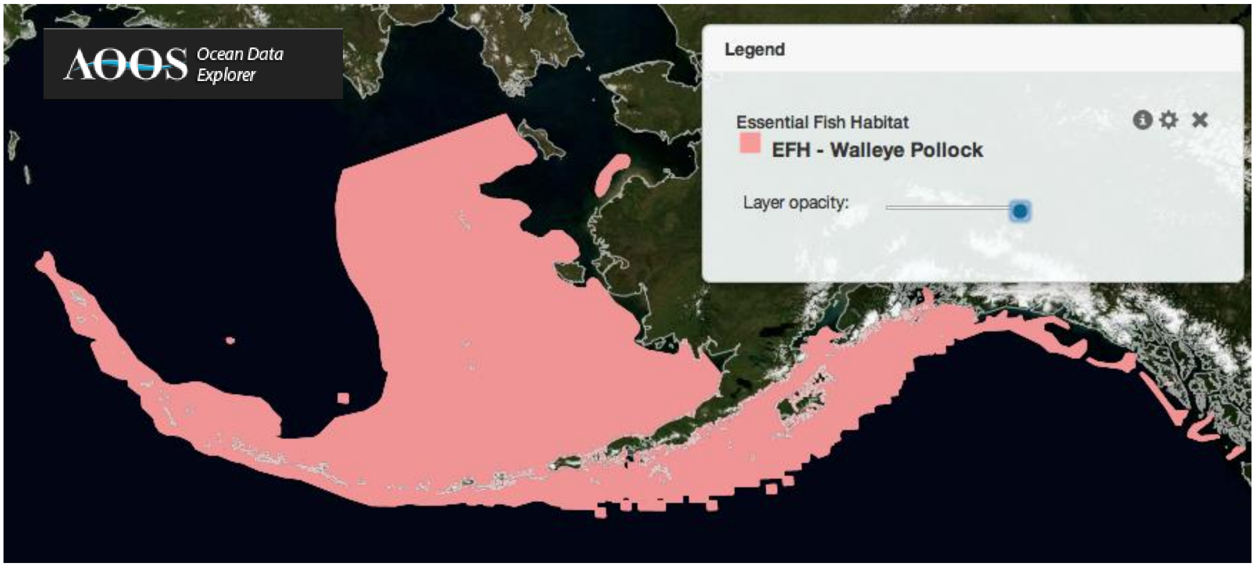
In addition to the spatial diversity of physical environments discussed above, this vast region is home to– at least 282 fish species (NOAA/NMFS/RACEBASE database, Mecklenburg *et al*., 2002), including at least 45 commercially harvested species and a larger number of invertebrate species, including five commercial crab species (Table 1). Not all of the fish and shellfish species found in these regions are equally sensitive to climate change. Temperature preferences and limits exist; changes in habitat, range shifts, predation and abundance of prey, and adaptive capacities will all contribute to the overall exposure and vulnerability to change for specific species in specific areas. Few species have been extensively studied; consequently, particular areas and species discussed are limited to the authors' collective understanding.

Section 1: Bering Sea Shelf *including Northern, Central and Southeastern*

The Bering Sea shelf is characterized by strong seasonal cross-shelf gradients consisting of the well-mixed inner domain (< 50 m), the stratified middle domain (50-100m) and the outer shelf (100-200 m) and slope (200-1500 m), which are separated by distinct oceanographic fronts along the 50 m, 100 m, and ~200 m depth contours (Coachman, 1986; Stabeno *et al*., 2001). In addition, there are strong north-south gradients primarily defined by sea ice characteristics in the winter and salinity and temperature gradients in the summer (Stabeno *et al*., 2012a; Stabeno *et al*., 2002a). Ice extent on the shelf determines the extent of the "cold pool", a bottom water mass (-1.9˚C to 2˚C) that is cooled to near freezing when the ice forms and remains on the middle shelf throughout most of the following summer after the ice melts back in the spring. This cold water is an effective barrier to many subarctic (boreal) fish species in the eastern Bering Sea, whose distribution over large parts of the shelf varies in response to changes in the cold pool (Kotwicki and Lauth, 2013; Mueter and Litzow, 2008; Spencer, 2008). Along the coast, freshwater discharge influences physical and biological processes for nearshore areas.

Below we provide brief introductions to resident species across the Bering Sea shelf, and then we identify specific physical drivers, critical or sensitive habitat areas, and unique populations within each (northern, nearshore, central and southeastern) sub-region and reviewed for potential climate-mediated vulnerabilities.

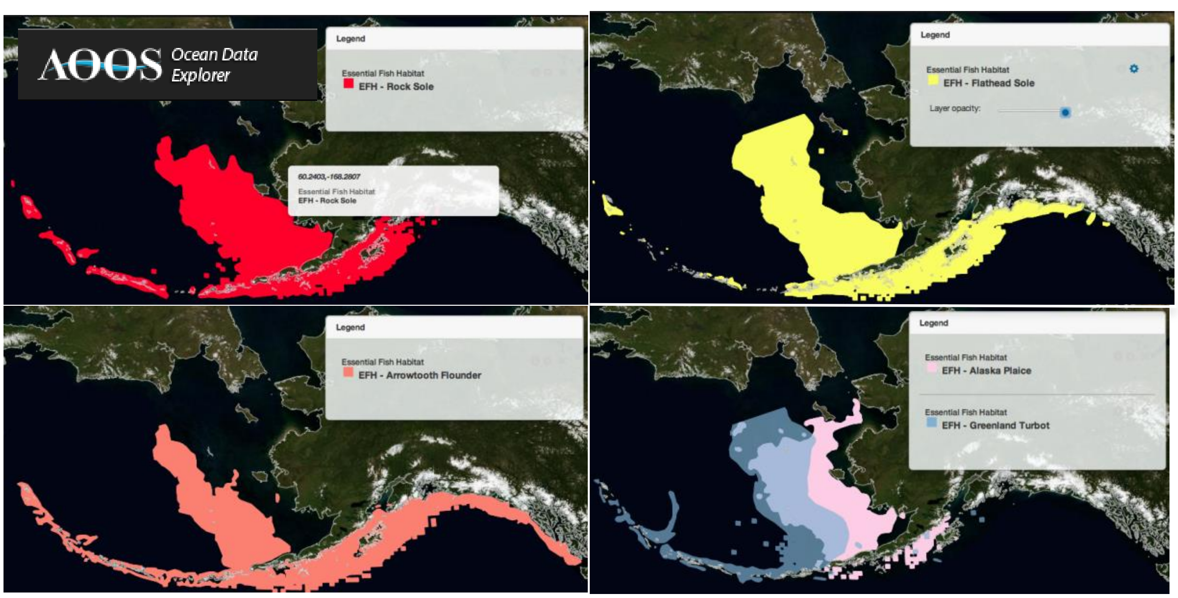
Section 1.1: Species Resident Across the Bering Sea Shelf



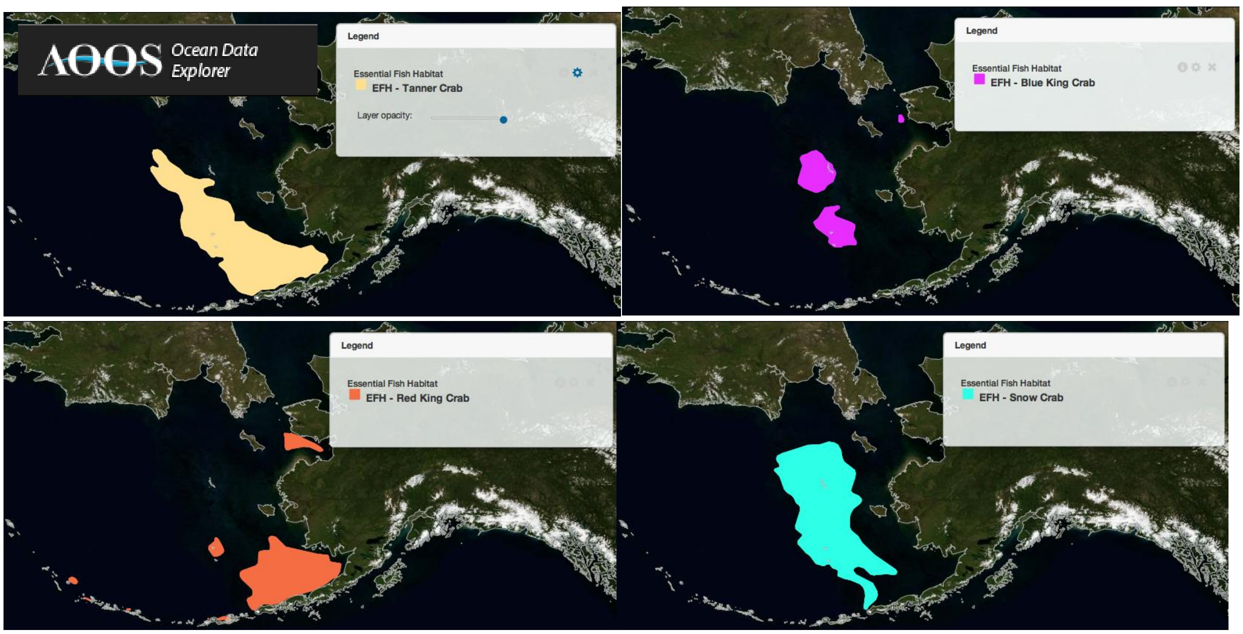
Walleye pollock in the eastern Bering Sea support the largest single-species fishery in the US and play a key role as a forage species for other fish, seabirds and marine mammals. Survival and recruitment of pollock and their zooplankton prey are regulated by complex ecological relationships, which include temperature and seasonal ice cover. For example, primary production peaks in late May/early June in warm years (ice absent or retreated before March 15) and peaks as ice retreats in cold years (ice present after March 15) (Brown and Arrigo 2013; Hunt *et al.*, 2002, 2011; Sigler *et al.*, 2014). As a result, subarctic productivity and the interrelationships of climate, ice, phytoplankton, zooplankton and juvenile pollock are complex (Baier and Napp, 2003; Coyle *et al.*, 2011; Hunt *et al.*, 2011). Timing and location effects are, in large part, responsible for the match or mismatch between fish larvae, their prey and their predators (Siddon *et al.*, 2013; Sigler *et al.*, in review).

Recent work suggests that juvenile pollock are particularly vulnerable to temperature-mediated changes in zooplankton prey composition. Exceptionally warm years in the early 2000s were associated with either an early ice retreat or a complete lack of ice on the southeastern Bering Sea shelf. For reasons not fully understood, these conditions are associated with high abundances of smaller zooplankton, but a relative lack of large, lipid-rich zooplankton on the shelf (Baier and Napp, 2003; Coyle *et al.*, 2011). The latter are important prey for late larval and early juvenile pollock as they accumulate energy reserves for the winter (Heintz *et al.*, 2013; Siddon *et al.*, 2013), and the lack of large zooplankton in these warm years was associated with very poor overwinter survival and low abundances of pollock in the following years. In contrast, the abundance of large, lipid-rich zooplankton (such as large copepods and krill) increased during subsequent cold years (2007-2013), providing better feeding conditions for larval and juvenile walleye pollock. This resulted in a much higher energy density of age-0 walleye pollock during late summer (Heintz *et al.*, 2013), as well as reduced cannibalism and predation on age-0 pollock (Coyle *et al.*, 2011; Hunt *et al.*, 2011). As a result, more pollock survived the winter and contributed to a rapid recovery of the population. Therefore it is reasonable to predict that future abundances of pollock are likely to decline if the Bering Sea experiences warm years more frequently in the future as predicted by global climate models (Mueter *et al.*, 2011). This effect may be further exacerbated if, as predicted (Hunsicker *et al.*, 2013), the overlap between juvenile pollock and arrowtooth flounder, a major predator on juvenile pollock, increases in warm years as arrowtooth flounder expand in warmer, shallower areas of the shelf.

Pacific cod are likely to experience similar dynamics as walleye pollock as their variability in year class strength is nearly synchronous. Both species are supported by strong year classes occurring every 4-6 years and both species had very poor survival of the cohorts spawned during the exceptionally warm years from 2001 to 2005. The common mechanism regulating recruitment in both species on the eastern Bering Sea shelf is likely related to the effects of climate conditions on prey quality and quantity, and hence on the condition (caloric density) of gadids prior to winter, which is higher during cool years (Farley *et al.* In Press).



Some flatfishes, including arrowtooth flounder, flathead sole and rock sole appear to be less susceptible to temperature variability, but their year-class success has been linked to variability in winds. Specifically, wind conditions that are favorable to the advection of larval flatfish towards shallow, nearshore areas that serve as nurseries for juvenile flatfish are associated with enhanced survival of the affected year class (Wilderbuer *et al.*, 2013; Wilderbuer *et al.*, 2002). Such winds have been more prevalent since 1989, and have contributed to increases in the abundance and biomass of all three species. Projections of future winds from global climate models suggests more frequent occurrences of onshelf winds over the eastern Bering Sea shelf in the coming decades (Wilderbuer *et al.* 2013). However, at least for northern rock sole, this effect is moderated because the survival of young rock sole is reduced when the abundance of adults increases and the overall net effect on rock sole abundances may be small.



Crab

Snow crab are widely distributed in subarctic and arctic regions, including the northwestern Pacific, Bering Sea, parts of the Arctic, northwest Atlantic south to Maine, and the west coast of Greenland. In the eastern Bering Sea, snow crab are broadly distributed on the middle and outer domains. They are adapted to cold conditions and are expected to decline in a warming climate. Maturity is delayed, fecundity is reduced, and the survival of some stages may be enhanced under warmer conditions (Kruse *et al.*, 2007); early benthic juveniles prefer temperatures below 2˚C, corresponding to conditions in the cold pool. This temperature link is supported by a negative relationship between regional temperatures and the number of snow crab in subsequent years (Marcello *et al.*, 2012; Szuwalski and Punt, 2013). This dependence of the juvenile stages on cold bottom temperatures can result in what has been described as an "environmental ratchet" (Orensanz *et al.*, 2004). Following a reduction in the spatial extent of the cold pool, juvenile snow crab are restricted to the colder, northern parts of the shelf. At the same time predatory fish such as Pacific cod expand into areas formerly occupied by the cold pool (Mueter and Litzow, 2008), inhibiting the southward expansion of snow crab even when intermittent cold conditions return. Moreover, the associated reduction in spawning biomass on the southern parts of the shelf make it more difficult for snow crab to become re-established in the southern area because larvae tend to drift northward with the prevailing currents (Parada *et al.*, 2010). Therefore, intermittent warming can result in a pronounced retraction of snow crab to the North that may be difficult to reverse.

Blue King Crab have a discontinuous distribution in the eastern Bering Sea shelf, primarily being distributed in waters surrounding the Pribilof Islands, St. Matthew Island, and St. Lawrence Island. Beyond the Bering Sea and Aleutian Islands region, they are further distributed southeast to the Gulf of Alaska and southwest to the Sea of Okhotsk and Japan. Mechanisms regulating recruitment are unknown, but commercially fished stocks around St. Matthew and Pribilof Islands have fluctuated widely. The St. Matthew Island stock recovered from an apparent mass die-off from unknown reasons during 1998-1999 (Zheng and Kruse 2002), whereas the Pribilof Islands stock was declared “overfished” in 2002, presumptively owing to reproductive failure, and it has failed to recover while being managed under a conservative stock rebuilding plan (NPFMC 2013). Recent efforts to learn more about regional ocean acidification have shown evidence of carbonate mineral dissolution in cold, highly productive areas of the northern shelf in the vicinity of snow crab and blue king crab habitats (Cross *et al.* 2014). Projections by Mathis, Cross, and colleagues show that undersaturated conditions with respect to aragonite and possibly carbonate are likely to continue to persist and cover the entire continental shelf in the coming century (Mathis *et al.*, 2014). As blue king crab habitats are associated with islands, they have little scope for northward displacement.

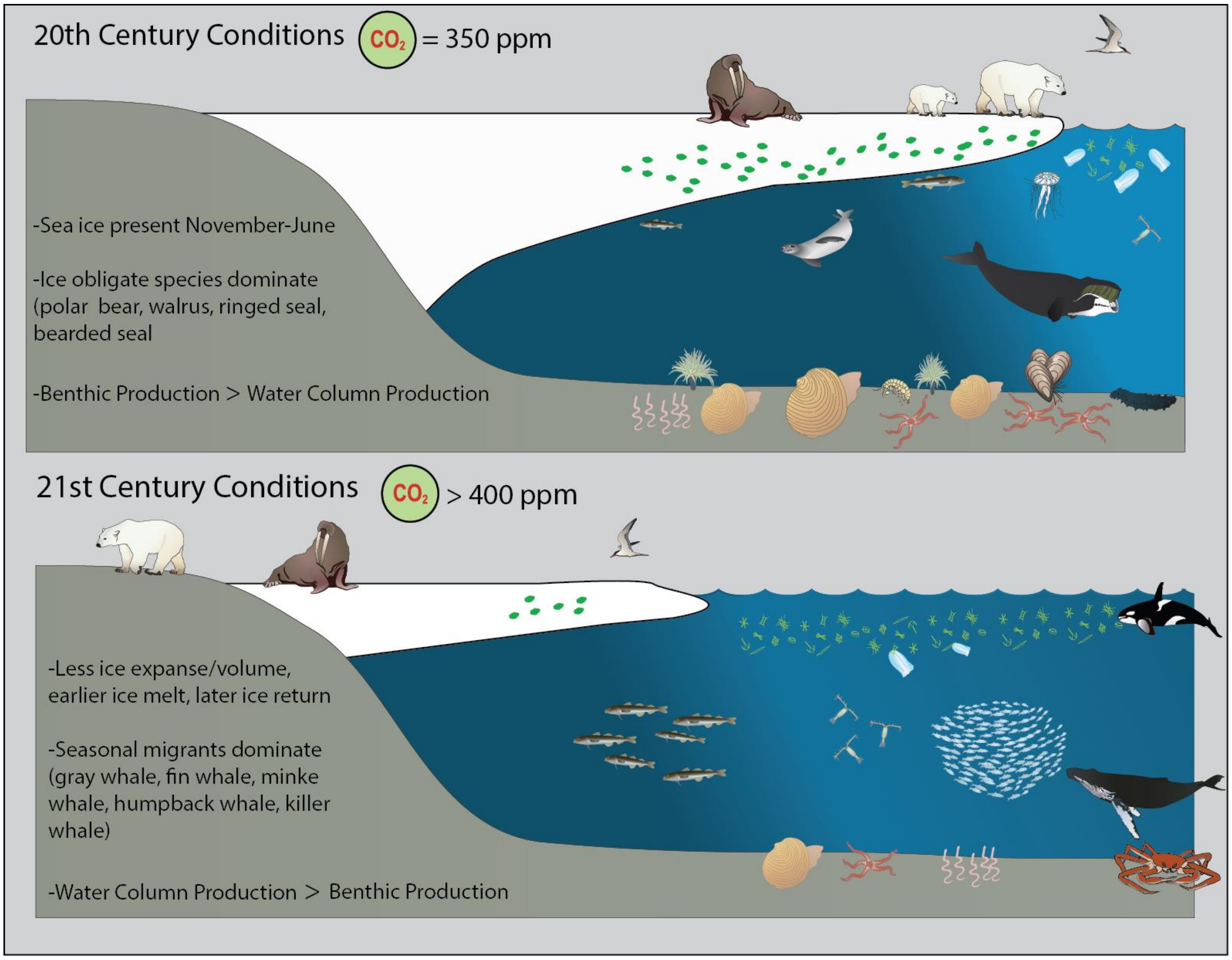
Red king crab *(Paralithodes camtschaticus)* are distributed on the continental shelf of the North Pacific Ocean from British Columbia to Japan and into the Bering Sea. They range in depth from the intertidal zone to 200 meters or more. In the Bering Sea and Aleutian Islands region, prominent stocks are located in the Aleutian Islands, Bristol Bay, Pribilof Islands, and Norton Sound. All stocks have experienced wide swings in abundance; at least some of this variability has been attributed to fishing effects (Kruse *et al.* 1996, Orensanz *et al.* 1998). The largest of these stocks resides in Bristol Bay, where a foreign commercial fishery began in the 1930s, which transitioned to a domestic fishery in the 1970s (NPFMC 2013). After peak landings in 1980, this fishery was closed in 1983 because of stock collapse. Additional fishery closures in 1994 and 1995 were associated with depressed stocks. Populations successfully recovered in 2003 after implementation of a stock rebuilding plan, which involved reduced harvest rates, fishery thresholds, bycatch caps for groundfish fisheries, and area closures to trawling (Kruse *et al.* 2010). Likewise, the Norton Sound red king crab stock responded well to more conservative management after a brief period of high harvest rates in the late 1970s, and the Pribilof Island stock responded well to fishery closures after declines in the late 1990s (NPFMC 2013). The Pribilof Islands fishery remains closed owing to concerns about bycatch of blue king crab. On the other hand, stocks in the Aleutian Islands once supported large fisheries, but they collapsed and remain depleted after prolonged fishery closures.

In addition to fishing effects, several hypotheses have emerged about climate and ecological effects on red king crab dynamics. Patterns in recruitment of Bristol Bay red king crab bear some resemblance to patterns in the Pacific Decadal Oscillation (PDO), a regional index of changes in temperature (Zheng and Kruse 2006, Kruse 2007). In association with warming temperatures since the 1970s, the center of the population distribution shifted from north of Unimak Island to the northeast, perhaps compromising the delivery of settling larvae to nursery areas on inner Bristol Bay (Loher and Armstrong 2005). Strong recruitments generally occurred when the spawning stock was primarily located in southwestern Bristol Bay. Partial return movement to the southwest were associated reversals in the PDO in 1989-1990 and 1999-2000 (Zheng and Kruse 2006) and 2007-2013 (J. Zheng, Alaska Department of Fish &Game, pers. comm.). Another hypothesized climate link concerns prey species composition. Studies in Auke Bay in Southeast Alaska demonstrated that the spring bloom was predominated by *Thalassiosira* diatoms in years of weak winds, whereas a more diverse phytoplankton community existed in years with a more well-mixed water column (Bienfang and Ziemann 1995). A diet including *Thalassiosira* appears to promote growth of red king crab larvae (Paul *et al.* 1990), and a diet of *Artemia spp.* and *Thalassiosira nordenskioeldii* significantly improved survival of laboratory-reared red king crab larvae compared to those reared on *Artemia* only (Persselin and Daly 2010). It was postulated that, when the PDO is positive, stronger winds associated with the Aleutian Low result in a more mixed water column, which compromises feeding by king crab larvae (Zheng and Kruse 2006, Kruse 2007). Finally, there are negative associations between red king crab recruitment and the biomass of groundfish predators, Pacific cod and yellowfin sole. However, field studies have not been undertaken to validate predation as a key mechanism.

A stage-structured red king crab bioeconomic model was developed to capture hypotheses regarding the impact of ocean acidification on the survival of pre-recruit crab (Punt *et al.*, 2014). The model was parameterized using life history and survival data for red king crab derived from experiments conducted at the National Marine Fisheries Service Kodiak laboratory (Long *et al.*, 2013 a, b). Expected yields and profits were projected to decline over the next 50–100 years given reductions in pre-recruit survival due to decreasing ocean pH levels over time (Punt *et al.*, 2014).

Box 2.1: **A restructuring of the foodweb in the northern Bering Sea**

It is thought that where sea ice has diminished such as in the most northern Bering Sea, major ecological shifts can be expected (Grebmeier et al. 2006), as shown in the twin diagrams below. Less extensive sea ice will lead to lower deposition of sea ice and spring bloom algae (bottom), and a lower biomass benthic community. Fish and zooplankton will increase in importance and pelagic feeding whales such as orcas and humpbacks will become more important than sea ice-associated bowhead whales and benthic feeding pinnipeds.



Section 2: Northern Bering Sea North of 60°N

The present climate of the northern Bering Sea typically features prevailing winds from the northeast bringing cold air masses of continental or arctic origin in the winter, and more variable winds in the summer with air masses of maritime origin. The consequence is a prominent seasonal cycle in sea ice where the presence of sea ice dictates key aspects of the ecosystem structure and function. Climate models project that the northern Bering Sea will continue to have extensive winter and spring sea ice, although ice thickness may decrease (Stabeno *et al.*, 2012a). Likewise, the summer cold pool over the northeastern middle shelf will continue to be a barrier to many species, such as pollock, that cannot tolerate freezing water.

However, because of how and where the cold pool forms, species affected by it may be able to migrate seasonally farther north, if they inhabit the outer shelf, rather than the middle shelf (Hollowed *et al.*, 2012; Kotwicki and Lauth, 2013), or if they use warmer nearshore corridors.

Another key ecological organizing principle for the northern Bering Sea is that the shallow productive waters lead to strong pelagic-benthic coupling, and deposition of fresh chlorophyll coinciding with the spring bloom (Cooper *et al.* 2002; 2012). This sea ice and water column bloom supports extensive macrobenthic invertebrate communities that serve as food resources for diving mammals and birds such as gray whales, bearded seals, eiders, and walruses (reviewed in Grebmeier 2012). Between St. Lawrence Island and Bering Strait, the persistence of seasonal sea ice has significantly declined over the past three decades, although between St. Matthew Island and St. Lawrence Island, no significant decreases, and in some cases, modest increases, in sea ice persistence have been observed (Frey *et al.* 2014). It is thought that where sea ice has diminished, such as in the most northern Bering Sea, major ecological shifts can be expected (Grebmeier *et al.* 2006). This conceptual shift is illustrated in the graphic above.

In addition to changes in sea temperature and the spatial distribution of the cold pool, already seasonally persistent low pH in parts of the northern Bering Sea are likely to be further impacted by ocean acidification due to cold temperatures and freshwater melt. This may be influencing the changes in clam populations that have observed southwest of St. Lawrence Island, which are in important foraging areas for spectacled eiders and walruses.

Section 2.1: Species in the Northern Bering Sea

Adapted to living in Arctic waters, those remarkable species that can tolerate freezing seawater – including Arctic cod, Bering flounder, Greenland turbot, snow and blue king crab – may pay a metabolic cost for their ability to produce antifreeze proteins and grow more slowly at higher temperatures (Jørgen S Christiansen, University of Tromsø, pers. comm). Although they may be able to tolerate warmer temperatures, cold-adapted species are likely to be outcompeted by more temperate species as water temperatures increase in the northern Bering Sea, especially as their preferred habitat during part or all of their life history shrinks or disappears (Hop and Gjøsæter, 2013; Hollowed *et al.*, 2013).

Section 3: Shallow, nearshore waters

Shallow, nearshore waters may be particularly sensitive to changing air temperatures, affecting free-swimming, benthic and attached organisms in the littoral zone, including juvenile fish and shellfish that use the nearshore environment, i.e., regions of less than ~20 meters depth, as nursery areas. Such warming may be particularly pronounced in coastal areas that have land-fast ice in the winter such as Norton Sound and St. Lawrence Island because an earlier ice melt can greatly increase the length of time during which shallow waters are exposed to solar radiation. Cold-adapted species using these areas may not be able to adapt to the substantial warming that is predicted to occur in these areas. In Norton Sound, where the average depth is only 18 meters, benthic communities may transition from the current invertebrate-dominated regime to one more suited to juvenile groundfish (Hamazaki *et al.* 2005).

In addition to the direct effects of temperature, nearshore areas that are subject to the influence of larger river discharges, including the Yukon-Kuskokwim Delta will also be impacted by other climate driven processes. For example, changes in timing and volume of freshwater runoff will lower nearshore salinities, and increase nutrient and sediment loading; increased exposure to storms and wave actions will increases erosion and associated hazards, including habitat alteration or damage. These effects will be more pronounced where terrestrial inputs are larger, such as along the mainland coast downstream of large river systems.

Section 3.1: Species with critical life cycle phases in shallow, nearshore waters--Salmon

The timing of spawning, incubation, emergence and emigration in the life cycle of the Pacific salmon species (*Oncorhynchus* spp.) are known to be temperature dependent, and salmon are therefore sensitive to changes in climate. In these anadromous species, the success of each year class is dependent on timely arrival of each stage of the life cycle at a series of widely geographically separated localities. The localities and the amount of time between each stage depend on the species and the life history patterns of populations within the species. In Alaska the six species are roughly divisible into two life history patterns based on the length of the freshwater stage. Chinook, coho, and sockeye salmon and steelhead go to sea after the first year of life, and pink and chum salmon enter the sea during the first year of life. Exceptions are noted for Chinook and sockeye salmon populations where some individuals emigrate during the first year of life, but these are in relatively small numbers statewide. Nonetheless for all salmon species, the nature and intensity of the responses to climate change will be largely functions of life history patterns.

The timing of the stages in the life cycles of salmon necessarily evolved in synchrony with annual seasonal cycles to provide each stage the necessary ambient temperature regime, among other factors essential to completing the life cycle. Physical cues from the freshwater and brackish water environments interact with physiological processes to enable the migratory behavior that brings the young salmon to the coastal marine environment at a time that on average coincides with favorable conditions for growth and survival. Salmon transitioning between freshwater and marine environments are particularly sensitive to changes in the volume, temperature and composition of discharged waters. High salinities are limiting to freshwater species and require gradual transition for anadromous species such as when juvenile salmon first enter marine environment. In the northern Bering Sea, land-fast ice may provide sheltered areas of low salinity water to help ease with the transition (Charlie Lean, Norton Sound Economic Development Corporation, pers. comm.).

As a working hypothesis of how climate may affect salmon populations in coastal waters, changes in climate that disrupt the synchrony between entry of the young salmon into the marine environment and the processes in the marine environment that are critically important to salmon survival such as the spring bloom will lower the survival of a year class. The potential for changes in the timing of the spring bloom to impact salmon survival is exemplified by the observed positive association between the onset of the bloom and pink salmon survival as has been observed in other parts of the Pacific (Cooney *et al.* 2001, Malick *et al.* 2015). As more generally stated, the Critical Size and Period Hypothesis, CSP, holds that salmon year class strength is largely determined during the first ninety or so days after they enter the nearshore marine environments (Farley *et al.* 2007, Beamish *et al.* 2004, Karpenko 1998, Pearcy 1992, Parker 1968). After entering the sea, salmon must achieve a critical size by end of the first summer in order to survive through the winter (Beamish and Mahnken 1999, 2001, Beamish *et al.* 2011).

Nearshore temperature conditions during the early ocean phase have also been linked to survival rates of multiple sockeye, pink, and chum salmon stocks in the Northeast Pacific with enhanced survival in Alaskan stocks when temperatures are above average (Mueter *et al.*, 2002). Adult salmon returning to their natal streams may face a potential bottleneck due to enhanced susceptibility to predation and disease, both of which may be temperature dependent. Also, changes in temperature and salinity could change the timing of adult upstream migration. Models based on environmental factors during multiple lifecycle phases have been developed that explain a large fraction of variability in the abundance and escapement of western Alaska chum salmon (Shotwell *et al.* 2005).

Section 4: Central and Southeast Bering Sea South of 60° N

Ice and near-bottom temperature conditions on the southeast Bering Sea shelf, south of about 60˚N, are likely to be most susceptible to climate change, with potentially wide-ranging effects on the marine ecosystem. The southern extent of ice on the shelf is extremely variable as exemplified by contrasting warm and cold conditions during recent years, ranging from very little or no ice south of 60˚N to heavy ice cover over the shelf extending as far as the Alaska Peninsula and Bristol Bay (Stabeno *et al.*, 2012b).

In the context of a warming climate, the shelf area of the southeastern Bering is the region where current interannual ecosystem variability is highest and where changes are expected to be most dramatic, as demonstrated by the recent warm/cold periods-- with fewer cold years (as in 2007-2013) and more warm years (as in 2001-2005; Stabeno *et al.*, 2012b).

Near-bottom temperature conditions, particularly the Cold Pool, limit the northern extent of many subarctic species; a more extensive cold pool is also associated with an expansion of Arctic species southward onto the middle shelf, including Arctic cod and snow crab. Changes in the spatial distribution of demersal species will have profound effects on trophic dynamics on the southern middle shelf and is likely to result in many indirect effects on the abundance of individual species. For example, increased predation can lead to altered foraging patterns associated with changes in the relative distribution of predatory fish such as arrowtooth flounder, Pacific cod, and adult walleye pollock and their prey (Chen *et al.*, 2012; Hunsicker *et al.*, 2013; Mueter *et al.*, 2011; Spencer, 2008).

In addition to direct effects on spatial distribution, and related effects on trophic interactions, ice and temperature conditions on the shelf have recently been shown to affect the abundance and species composition of zooplankton prey on the middle and outer shelf (Coyle *et al.*, 2011; Hunt *et al.*, 2011) with consequences for the growth and survival of juvenile pollock as described in section 1.2. The primary processes of concern in this area are the extent of winter-time ice, and the timing of ice melt in the spring. Secondarily, this area is susceptible to changes in the strength and trajectory of storms during summer and fall and their effects on mixing and stratification.

In combination, reductions in the cold pool area, affecting the distribution of demersal fish and shellfish, and impacts at the bottom of the food chain related to a lack of ice or its early retreat can drastically alter trophic interactions throughout the food web. Species that depend on or respond to strong bottom-up forcing, particularly if these bottom-up effects are related to temperature variability, will tend to be more vulnerable to climate change. Examples include walleye pollock, Pacific herring, and salmon. There is some weak evidence of a northward shift in overwintering locations of Pacific herring *(Clupea pallasii)* north into the Bering Sea (Tojo *et al.* 2007).

Section 4.1: Species in Central and Southeast Bering Sea

Pacific herring are distributed throughout the Pacific Ocean, from the Yellow Sea in the west and Baja California in the east, north through the Bering Sea to the Chukchi and Beaufort Seas. Herring are an important forage species for many other fish species, marine mammals, and seabirds. They feed largely on phytoplankton and zooplankton. Herring spawn in shallow subtidal or intertidal areas along coastlines each spring and then move offshore to feed. In fall, they move to deeper overwintering grounds. Analyses of herring bycatch in Bering Sea trawl fisheries indicates two overwintering areas – a northern area to the northwest of the Pribilof Islands and a southern area north of Unimak Pass (Tojo *et al.* 2007). The timing of the spawning migration in spring is largely a function of climate variability; specifically, heavy sea ice extent and cold ocean temperatures in March and April cause a delay in the timing of herring spawning (Tojo 2006). Contemporary commercial fisheries target the arrival of pre-spawning herring, which are harvested mainly for their valuable roe. In the eastern Bering Sea, the largest fishery is prosecuted in northern Bristol Bay (Togiak), but smaller fisheries including subsistence herring fisheries (Raymond-Yakoubian 2013) occur along the coast north to Norton Sound an occasionally farther north to Port Clarence (Bue *et al.* 2011). Recruitment to the Bristol Bay stock is strongly cyclical. Recruitment is relatively independent of stock size (Wespestad and Gunderson 1991, Zheng 1996), consistent with environmental control of recruitment. Above average recruitment often occurs in warm years when winds favor retention indicated by low transport velocity toward shore (Wespestad and Gunderson 1991).

Tanner crab are distributed on the continental shelf of the North Pacific Ocean from Oregon, north into the Bering Sea, and west to Kamchatka. In the eastern Bering Sea, Tanner crab are mainly distributed from Bristol Bay to waters around the Pribilof Islands. As with most crab populations off Alaska, the eastern Bering Sea stock of Tanner crab experienced a history of large-scale variability in recruitment and adult stock size, leading to a "boom and bust" fishery (NPFMC 2013). A 13-14 yr cycle in both fishery recruitment and adult population size has been interpreted to indicate that long-term environmental variability may play a strong role in recruitment strength (Zheng & Kruse 2003). Some studies found statistically significant relationships with stronger Tanner crab recruitment: (1) warmer bottom temperatures, which may promote gonadal development and embryo incubation, and (2) northeasterly winds, which may favor retention of larvae in fine sediments located offshore (Rosenkranz *et al.* 1998, 2001). A third potential relationship with warm sea surface temperatures during the larval period, thought to favor copepod nauplii production, was marginally non-significant. However, a recent modeling analysis of Tanner crab recruitment mechanisms using a Regional Ocean Modeling System generally failed to confirm these earlier findings (Richar *et al.*, in prep.). The best model formulation based on larval retention in the survey area and settlement in bottom temperatures >1° C explained 37% of the variability in Tanner crab recruitment. The Pribilof Islands area appears to have become much more important for larval retention than Bristol Bay after 1990, consistent with an observed geographic shift in fishery productivity (Richar *et al.* 2015). Weak support was found for benefits of warmer sea surface temperatures during the larval stage on subsequent recruitment. Effects of predation on Tanner crab appear to be complex. Groundfish, such as Pacific cod, eat large quantities of juvenile Tanner crab (Livingston 1989). However, there is no evidence of a consistent negative relationship between Tanner crab recruitment and cod abundance (Rosekranz *et al.* 2001; Richar *et al.*, in prep.). Rather, recent evidence indicates that cod were the major predator of Tanner crab during the 1980s, while flathead sole became the predominant predator in the 1990s (Richar *et al.*, in prep.). Non-linear associations between cod and sole predation on Tanner crab are largely attributable to large shifts in the geographic distribution of these two predators on the continental shelf.

Section 5: The Aleutian Islands

The Aleutian Islands stretch over 1900 km from the Alaska Peninsula in the east to the Commander Islands in the west. The Aleutian Islands are characterized by a strong east to west gradient and have been divided into three ecoregions: eastern (east of Samalga Pass), central (Samalga Pass to 177˚E), and western (Zador, 2013). In particular, a pronounced climatological and faunal break near Samalga Pass has been documented (Hunt and Stabeno, 2005).

The potential effects of climate change in the Aleutian Islands are highly uncertain, but we do know that the intermediate waters along the continental slope of the Aleutians (100-200 m) are highly susceptible to the effects of ocean acidification. Increasing levels of anthropogenic CO_2 in the atmosphere contribute to aragonite and calcite under-saturation in these waters, with the saturation depth rising to above 200 m (Feely *et al.*, 2002). Under-saturation makes it more difficult for organisms to form skeletal structures, consisting of aragonite or calcite, with potentially important consequences for shellfish such as crab, deep-sea corals and other species. Even before anthropogenic CO_2 instigated shoaling in the aragonite and calcite under-saturation horizons, these horizons were shallow in the North Pacific Ocean (Feely *et al.*, 2004); as a result, species, such as golden king crabs *(Lithodes aequispinus)* and deep-water corals that reside along the continental slope in the Aleutian Islands region have apparently evolved mechanisms to cope with under-saturation since before industrialization.

Section 6: Shallow passes such as Unimak Pass

In addition to warming sea temperatures, shifts in the extent of the southern cold pool, and ice coverage, wind is an important physical factor that drives critical processes impacting the lifecycle of several fish species. Flows through shallow water passes are highly susceptible to changes in wind magnitude and direction. Wind shifts may affect primary and secondary productivity in these passes, the direction and extent of advection of early life history stages through the passes, and the advection of early life history stages originating upstream or near these passes towards their nursery areas. For example, flow through Unimak Pass is susceptible to changes in regional winds, particular the frequency, direction and magnitude of zonal (east-west) winds, and freshwater discharge into the Gulf of Alaska, which drives variability in the Alaska Coastal Current. This current enters the Bering Sea from the Gulf of Alaska, transporting nutrients and plankton through Unimak Pass (Stabeno *et al.*, 2002b). The consistent, deep mixing of waters within Unimak Pass is an important contributor of nutrients to the Bering Sea shelf (Stabeno *et al.*, 2002b) and provides an important connection for plankton, including larval fishes, between the Gulf of Alaska and Bering Sea. Both surface and deep-water flows through Unimak Pass affect the transport of larval rock sole through Unimak Pass and onto the shelf (Lanksbury *et al.*, 2007). More generally, the distribution patterns of early life history stages of several fish species, including Pacific cod, northern rock sole and flathead sole are affected by flow through the pass (Siddon *et al.*, 2011).

The region includes important spawning areas for walleye pollock, Pacific cod, and several flatfish species (Bacheler *et al.*, 2012; Smart *et al.*, 2012), which implies that their pelagic eggs and larvae are particularly vulnerable to variability in currents flowing through Unimak Pass. Westerly wind anomalies and reduced freshwater discharge in the Gulf suppress northward transport through the Pass. How wind-driven or geostrophic flows through this or other shallow passes will change is currently not known; dynamical models of these flows require grids that are far finer than those of current global climate models. The projections from these climate models for the eastern Bering Sea shelf suggest a modest increase in the frequency of on-shelf winds in the coming decades (Wilderbuer *et al.* 2013), conditions that tend to be associated with decreased flow through Unimak Pass (Stabeno *et al.* 2002b). How these changes affect productivity is unknown, although more vigorous mixing in the Pass may be expected to enhance local production.

Along the continental slope of the Aleutian Islands, we know little about where and when fish and shellfish spawn and where important nursery areas are located (far less than is known in the Bering Sea). However, given that small changes in advection may advect pelagic eggs and larvae over long distances, combined with a narrow continental shelf and slope around the islands, there is a potential for eggs and larvae to be advected away from favorable nursery areas if dispersal patterns are modified as a result of climate change. Specific areas cannot be identified at present because critical spawning and nursery areas have not been identified in this region.

Section 6.1: Species along the SE shelf and along the Aleutians vulnerable to changes in advection

Flatfish, crab, and other species with strictly benthic early life history stages are particularly susceptible to changes in advection (Petitgas *et al.*, 2013) and recruitment success for some flatfish species (Wilderbuer *et al.*, 2013; Wilderbuer *et al.*, 2002), as well as snow (Parada *et al.*, 2010) and Tanner crab (Richar *et al.*, 2015), in the eastern Bering Sea have been linked to climate-mediated variability in connectivity between spawning and settlement. Climate-driven changes in larval dispersal are largely unknown because of the uncertainty in the effects of climate change on advection. Climate change effects on critical areas and on the dispersal pathways between spawning and settlement (nursery) areas makes species with benthic early life-history stages particularly susceptible to climate change. Species with more specific habitat requirements for spawning and nurseries have been hypothesized to display bottlenecks in their life cycle because of the requirement for connectivity between these areas (Petitgas *et al.*, 2013).

Crab larvae have been studied in the region, and a northeastward displacement of mature female red king crabs from north of Unimak Pass to central Bristol Bay has been hypothesized to result in advection of crab larvae past prime nursery grounds in inner Bristol Bay (Loher and Armstrong 2005, Zheng and Kruse 2006). Increased trawl survey catches of red king crab north of the Bristol Bay management district is consistent with this conjecture.

BOX 2.2 : Connecting fisheries ecology to the commercial fishing industry

The Aleutian and Bering Sea commercial fishing industry is exposed to a suite of alterations associated with climate change, including changes in stock productivity, species range shifts, changes in storm timing or intensity, and cross-sector externalities:

- Stock productivity: changes to harvested species' population productivities associated with climate driven changes in survival or in prey fields may decrease harvest opportunities for some stocks, and could conceivably improve harvest opportunities on others (e.g. Brander 2007; Ainsworth *et al.* 2011; Blanchard *et al.* 2012); the predicted changes in specific stocks' productivities are not well understood at this time, however, reallocation of wealth amongst fisheries and communities associated with variable changes in stock productivity (or in access to stocks, see range shifts below) may have disproportionate impacts on some fishing communities or fleets (i.e., there will be winners and losers).
- Species range shifts: Marine species range shifts (e.g. Cheung *et al.* 2010; Pinsky and Fogarty 2012) may result in some harvested stocks moving into conflict with other ocean management policies such as essential fish habitat closures along the Aleutians (e.g. cold water corals). On the positive side, species range shifts may open up additional harvest opportunities, should harvestable stocks expand into U.S. waters, or should arctic taxa become profitable to harvest as access to northern waters improves with a warming ocean.
- Increased frequency and severity of storms (e.g. Ulbrich *et al.* 2008): loss of property, loss of fishing days, and loss of life may be exacerbated should a warmer ocean result in a stormier ocean, particularly for smaller-vessel fisheries such as nearshore salmon and crab fisheries, and groundfish catcher boats. Increases in coastal flooding could also threaten fishing community infrastructure.
- Increased access to northern waters may increase potential for conflicts between industries: increases in access to previously ice-protected waters may result in additional extractive industry development (e.g. ACIA 2004) such as additional gold mining pressure in Norton Sound and oil and gas development in arctic waters. The impacts of gold mining on crab and fish nursery habitat in Norton Sound is currently under investigation, however, due to the intensity of physical disturbance associated

with dredge mining in the coastal ocean, negative habitat impacts are likely. Spills from oil and gas development have potential to foul local marine ecosystems, potentially directly harming commercially viable stocks, or indirectly through consumer scares over contamination. Furthermore, polar shipping routes are expected to open up with diminishing sea ice extent and thickness (e.g. Ho 2010), increasing potential for ocean shipping related disasters, including those related to fossil fuel transport.

The adaptive capacity of the Aleutian and Bering Sea commercial fishing industry to alterations associated with climate change is not well understood. Presumably fishing communities with access to larger boats and capital to adjust their fishing portfolios will be better equipped to adapt to changes in harvest opportunities--in terms of quantity, location, and species mix-- than others. Furthermore, communities whose economic base is diversified beyond commercial fishing may be more resilient to decreases or changes in fishing revenue if stock productivity and access becomes redistributed in a warming ocean.

Table 1: Commercially exploited species and species complexes in the Bering Sea and Aleutian Island regions (NPFMC, 2013)

Common name	**Scientific name**
Gadids	
Walleye Pollock	*Gadus chalcogrammus*
Pacific cod	*Gadus macrocephalus*
Flatfish	
Yellowfin sole	*Limanda aspera*
Greenland turbot	*Reinhardtius hippoglossoides*
Arrowtooth flounder	*Atheresthes stomias*
Kamchatka flounder	*Atheresthes evermanni*
Northern/Southern rock sole	*Lepidopsetta polyxystra/bilineata*
Flathead sole / Bering flounder	*Hippoglossoides classodon/robustus*

Alaska plaice	*Pleuronectes quadrituberculatus*
Rockfish	
Pacific Ocean perch	*Sebastes alutus*
Northern rockfish	*Sebastes polyspinus*
Blackspotted/Rougheye rockfish	*Sebastes melanostictus/aleutianus*
Shortraker rockfish	*Sebastes borealis*
Salmon	
pink salmon	*Oncorhynchus gorbuscha*
coho salmon	*Oncorhynchus kisutch*
Chinook salmon	*Oncorhynchus tshawytscha*
chum salmon	*Oncorhynchus keta*
sockeye salmon	*Oncorhynchus nerka*
Other	
Atka mackerel	*Pleurogrammus monopterygius*
Sablefish	*Anoplopoma fimbria*
Pacific herring	*Clupea pallasii*
Other flatfish complex, including:	
Arctic flounder	*Liopsetta glacialis*

butter sole	*Isopsetta isolepis*
curlfin sole	*Pleuronectes decurrens*
deepsea sole	*Embassichths bathybius*
Dover sole	*Microstomus pacificus*
English sole	*Parophrys vetulus*
longhead dab	*Limanda proboscidea*
Pacific sanddab	*Citharichthys sordidus*
petrale sole	*Eopsetta jordani*
rex sole	*Glyptocephalus zachirus*
roughscale sole	*Clidodoerma asperrimum*
sand sole	*Psettichthys melanostictus*
slender sole	*Lyopsetta exilis*
starry flounder	*Platichthys stellatus*
Sakhalin sole	*Pleuronectes sakhalinensis*
Other rockfish complex, including:	
Shortspine thornyhead	*Sebastolobus alascanus*
Dusky rockfish	*Sebastes variabilis*
Red banded rockfish	*Sebastes babcocki*
Redstripe rockfish	*Sebastes proriger*

Harlequin rockfish	*Sebastes variegatus*
Sharpchin rockfish	*Sebastes zacentrus*
Yelloweye rockfish	*Sebastes ruberrimus*

Commercially exploited crab species in the Bering Sea and Aleutian Island regions (NPFMC, 2013)

Common name	**Scientific name**
snow crab	*Chionoecetes opilio*
Tanner crab	*Chionoecetes bairdi*
red king crab	*Paralithodes camtschaticus*
blue king crab	*Paralithodes platypus*
golden king crab	*Lithodes aequispinus*

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Chapter 4: Vulnerability of Subsistence Cultures, Harvests, and Community Sustainability

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Introduction

The objective of this vulnerability assessment of subsistence communities is to identify factors and processes local to the ABSI region. This assessment downscales from previous large-scale climate change vulnerability assessments (Weller and Lange 1999, ACIA 2004), while furthering advancements made by previous efforts dedicated to the Bering Strait region (BESIS 1997, Callaway 1999, Gadamus 2013). This document is intended to provide a basis for further involvement of stakeholders, and to identify information gaps, research questions, and policy directions. We recognize the need for further development of some topics here included, and the likelihood that relevant topics and studies have been overlooked. Within these limits we hope to have advanced, even a modest amount, the understanding of the complex factors and processes through which climate-related changes interact with other changes affecting the well-being and sustainability of subsistence cultures in the ABSI region.

Human Communities in the Bering Sea and Aleutian Islands

Alaska rural communities are complex socio-ecological systems. Efforts to assess vulnerability of these communities to climate change require an understanding of how environmental variables interact with a range of ongoing socio-economic and cultural drivers of change. In assessing community vulnerability, it is also relevant to try to identify divergences between actual effects of climate change and local perceptions of changes associated with climate, which may be mediated by other drivers of change (Moerlein and Carothers 2012).

Alaska's rural communities are vibrant societies, with rich cultural heritage, and strong traditions of self-reliance and adaptation. These communities have access to diverse biological resources and rely on knowledge accumulated through generations to use these resources. Alaska Native cultures emphasize relationships among people and the natural world, and have a strong sense of place and identity. These values and knowledge make the sustainability of indigenous cultures and the maintenance of cultural diversity important, as consumerism and other distractions progressively compromise the well-being of modern societies. Alaska rural communities face many challenges in their efforts to co-exist within western society. This assessment refers to some of these challenges in an effort to identify interactions with climate change vulnerabilities. This exercise, however, should not be perceived as emphasizing the challenges, but rather as a pragmatic search for directions to promote the sustainability of these communities.

There are large uncertainties in forecasting effects of climate change on biological resources and on environmental and ecological systems. Therefore, it is difficult to forecast impacts of climate-related changes on rural communities and how they may react to such impacts. Furthermore, climate change is not the only, nor the most pressing, challenge that rural communities are facing. While Arctic indigenous peoples are experienced in dealing with environmental variability, social changes have represented serious challenges to the persistence of subsistence communities. Changing lifestyles, decreasing participation in subsistence activities, and economic and social changes are understood to be primary drivers reshaping subsistence patterns and practices in the Arctic (Moerlein 2012, Moerlein and Carothers 2012, Raymond-Yakoubian 2013, Raymond-Yakoubian et al. 2014, Raymond-Yakoubian and Raymond-Yakoubian 2015). Regulatory actions and competition for resources with other uses also affect harvest patterns, e.g. salmon bycatch. Understanding and forecasting consequences of climate changes on Alaska rural communities requires considerations of how these changes interact with ongoing changes on their social, economic, and cultural settings.

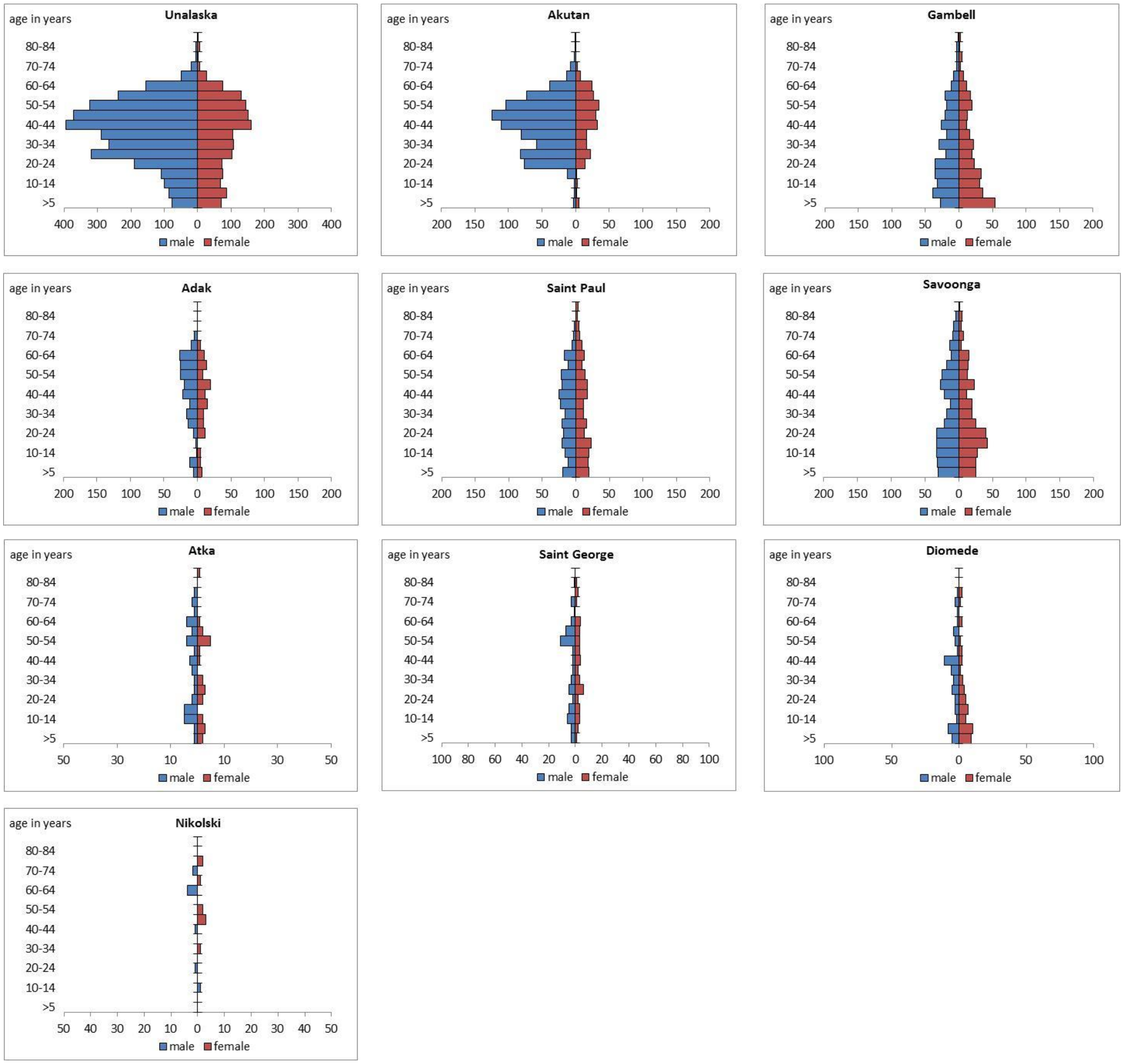
Several communities, most of which are primarily Alaska Native, are located in the Aleutian and Bering Sea Islands Landscape Conservation Cooperative (ABSI-LCC) region. Gambell, Savoonga, St. Paul, St. George, Akutan, Unalaska, Nikolski, Atka, and Adak are in the core of the ABSI region. Diomede, False Pass, Cold Bay, King Cove, Sand Point, and Nelson Lagoon are in the larger Aleutian-Bering Sea ecoregion. Gambell and Savoonga, on Saint Lawrence Island, are Siberian Yupik in heritage, Diomede, on Little Diomede Island, is of Inupiaq heritage, and the other communities in the region are of Unangax Aleut heritage. They differ in their historic, cultural, socio-economic, demographic, and ecological backgrounds, and these factors may affect their vulnerability and adaptability to climate change (Figure 1). Drivers and perceptions of change may also be affected by specific local factors and processes.

The sustainability and resilience of northern communities are largely based on social networks for the production and distribution of resources within and among communities (Magdanz *et al.* 2011, Reedy-Maschner and Maschner 2012). Sharing evolved as a highly effective social adaptive strategy used by communities living in extreme environments subject to variability in resource abundance (Berkes and Jolly 2001). Sharing has been traditionally recognized by communities as an important cultural value (Kawerak 2013a, Raymond-Yakoubian 2013, Raymond-Yakoubian and Raymond-Yakoubian 2015). Key people and places (or network nodes) play a vital role in the maintenance of the subsistence infrastructure (Wolfe *et al.* 2010) and distribution of resources throughout a community. Disruption of network nodes may disrupt economic and social systems.

Outmigration is a concern in much of rural Alaska and is a threat to smaller communities. Out-migration is more prominent for women and children, potentially leading to closure of local schools, and eventually the demise of small villages (Martin 2009, Lowe 2010). Age pyramids constricted at the base and deflated female ratios depict this dynamic (Figure 1). Population additions due to immigration of commercial fisherman and processing workers are composed mostly of males and are usually seasonal. These additions are more common in the commercial fishing centers of the southern part of the ABSI-LCC. However, because of their unbalanced demographic structure (Figure 1), their potential to contribute to demographic sustainability of communities is low. As a resident of Nelson Lagoon explained: "*Cannery helps, but it doesn't* *bring in families, only single men who bring in problems of their own*" (Reedy-Maschner and Maschner 2012: 197).

Unalaska (including Dutch Harbor) is the largest of the ten communities considered, with 2,273 people in households and a transient population of 2,103 people housed in group quarters supporting commercial fishing and processing. The Alaska Native population (355 people) represents 8% of the total Unalaska population (2010 population, U.S. Census Bureau 2011). The community of Akutan has a large seafood processing plant, which in 2010, housed 937 seasonal employees in group quarters. In Akutan, the 90 permanent residents include 76 Alaska Native people, representing 84% of the population (2010 population, U.S. Census Bureau 2011). Adak is a former Navy base, decommissioned in the mid-1990s, and acquired by The Aleut Corporation for redevelopment as a civilian community. The 2010 census showed a population of 326, with 217 of these being transients housed in group quarters. Of the 109 permanent residents 46, or 42%, are Alaska Natives. Except for Unalaska and Adak, Alaska Native people represent 83%–96% of the population in communities in the ABSI region.

Figure 1: Age and sex demographics for towns and villages within the study area.



Alaska rural communities, especially their Alaska Native residents, are primarily engaged in customary and traditional subsistence activities and rely on harvests of wild resources for nutrition, cultural identity, and social well-being. These communities have a subsistence-cash mixed economy, blending harvest, use of traditional foods, wage employment, and transfer payments that is part of their strategy as they adapt to changing political, economic and other conditions (Fall *et al.* 2013). Income generated by wage employment is necessary to procure fishing and hunting gear and supplies needed to carry out subsistence activities.

The economies of Unalaska, Akutan, Adak, and St. Paul are based on commercial fishing. Commercial fishing also plays a primary role in many subsistence-cash economies, and is an important factor in defining socio-economic contexts. Commercial fishing is a culturally sustainable path for Alaska Native communities to integrate into the wage economy, because fishing is compatible with traditional lifestyles (Wolfe 1984, Brakel, 2001). In rural communities, involvement in commercial fishing often increases local household harvest of fish and wildlife for subsistence (Wolfe *et al.* 2010). Such households own or have access to equipment, skills, knowledge, and cash needed to harvest wild foods. Local commercial fisheries also contribute a direct source of food because diverse products from commercial catches (both targeted species and incidental catches) are used for household consumption, especially halibut, salmon, crab, and octopus (up to 44 pounds per person per year) [Community Subsistence Information System (CSIS), http://www.adfg.alaska.gov/sb/CSIS/index.cfm?ADFG=main.home]. On the other hand, commercial fishing may reduce the abundance of subsistence resources and affect local and ecological processes.

In the ABSI region, Gambell, Savoonga, Nikolski, Atka, and St. George do not have high participation in commercial fisheries and rely on local services, government jobs, and transfer payments and subsistence. In Gambell and Savoonga, walrus ivory carving is an important source of income.

Bering Strait islands communities of Gambell, Savoonga, and Diomede, largely rely on harvests of marine mammals. In 2009, subsistence harvests at Savoonga were estimated at 948 edible lb/person and were composed of 45% walrus, 28% ice seals, 14% bowhead whale, 6% fish, 2% birds, 2% birds eggs, and 3% other resources (Tahbone and Trigg 2011). On the Pribilof Islands, the communities of St. Paul and St. George largely rely on harvests of halibut (about 40% of annual harvests), fur seal (about 30%), and Steller sea lion (5%–21%) [harvest survey conducted in 1994, http://www.adfg.alaska.gov/sb/CSIS/index.cfm?ADFG=main.home]. In the Aleutian communities, salmon (21%–45%), and halibut (10%–30%) are the main subsistence resources, while crabs (up to 11%), octopus (up to 10%), Steller sea lion (up to 23%), harbor seal (up to 11%), reindeer (up to 21%), and feral cattle (up to 23%) are important for some communities. Birds and eggs accounted for a small proportion of harvests (up to 4%) (http://www.adfg.alaska.gov/sb/CSIS/index.cfm?ADFG=main.home, Reedy-Maschner and Maschner 2012).

Interactions Among Ecological, Cultural, and Socio-Economic Factors

Socio-economic and cultural changes experienced by Alaska Native communities have affected their lifestyle and harvest patterns and may directly or indirectly interfere with perceptions of environmental change. Below we refer to some of these changes.

- Disruption of Native societies and economies by foreign Nation-states beginning with the Russian fur trade in 1741 and continuing to the present.
- Demographic collapse caused by introduced diseases and resulting famines, warfare, and population relocations forcing abandonment of traditional territories, affecting traditional harvest patterns and social structures.
- Imposed social and economic changes such as missions, schools, trading posts, and integration into worldwide market economies, resulted in the consolidation of small

settlements into larger villages, affecting traditional harvest patterns and social structures.

- Commercial whaling depleted stocks important for subsistence harvests.
- During World War II, Aleut villages west of Unimak Island were evacuated to remove civilians from the war zone. During the 3 years of the evacuation, many people died of diseases and malnourishment, including many elders, bearers of culture and knowledge. When people were allowed to return to the Aleutians at the end of the war, they found their villages in disarray from the U.S. military occupation. Several formerly viable communities were never reoccupied and are referred to by the descendants as "Lost Villages". Although monetary reparations were made in 1988, cultural and social consequences were not mendable.
- At many locations in the Bering Sea and Aleutian Islands, remains of military operations are significant sources of contamination and have actual and perceived associations with diseases such as cancer. Perceptions about the efficacy of past and on-going clean-up efforts are mixed. Contaminated locations may be close to communities (e.g., Gambell, Savoonga, Unalaska, Cold Bay, Adak) or on currently unoccupied islands used for subsistence activities or considered important cultural sites.
- Beginning in the 1950s, welfare programs and food stamps allowed survival independent of subsistence resources and contributed to changing food preferences and levels of participation in subsistence.
- Transition from dog teams to snow machines in the 1960s–1970s caused major changes in harvest patterns on St. Lawrence Island and elsewhere in Alaska because large amounts of fish or meat were no longer necessary to feed dog teams. Use of snow machines, and boat motors beginning in the 1920's, also contributed to dependency on cash income to acquire industrialized goods and fuel.
- Alaska National Interest Lands Conservation Act (ANILCA) and establishment of regional corporations promoted the cash economy. Participation in wage economy can limit the time available for subsistence pursuits.
- Modern infrastructure, industrialized goods, telecommunication systems, changing food preferences are resulting in indoor, sedentary lifestyles and increased material expectations.
- Modern education focuses on technical training and wage employment resulting in fewer avenues and opportunities to train youth for participation in a subsistence-cash mixed economy. General shift in social norms means youth are not necessarily expected to engage in subsistence activities. Language loss disconnects youth from Elders and less traditional knowledge is passed on.
- Many technologies are viewed as basic, yet expensive, necessities for subsistence activities. Buying gas, and acquiring and maintaining fishing and hunting gear is expensive and limits harvesting trips. Food stamps allow access to frozen, packaged food of low nutritional value while harvest pursuits of local resources become progressively more expensive.
- Rising costs of fuel and other necessities limit the number and length of harvest trips.

- Resource management systems are progressively more complex. There is growing polarization between rural and urban, commercial and subsistence interests.

Environmental Changes Reported by Alaska Arctic Communities

Projected climate changes in the Arctic include increased precipitation, shorter and warmer winters, decreased snow and ice cover, and increased storminess (Corell 2006). Environmental changes observed in recent decades include melting sea ice, rising sea levels, coastal erosion, permafrost thaw, and northward range extension of some sub-Arctic fish species (Hinzman *et al.* 2005).

In the spring walrus hunt on Saint Lawrence Island, three environmental variables (ice concentration, wind direction, and wind speed) accounted for 25%–32% of the daily variability in hunting effort and 18%–24% of the daily variability in harvest. High ice concentration and wind speeds were related to reduced hunting effort and harvest (Huntington *et al.* 2013b, Kawerak 2013d). Walrus distribution and abundance, societal factors, and interactions with other subsistence activities also affect hunting effort and success (for instance, a very successful spring bowhead whale hunt may be followed by relatively lower walrus harvest).

Some environmental changes and perceptions reported by Northwest Arctic communities (Moerlein 2012) are likely applicable to the Bering Sea and Aleutian Islands.

- Variability in environmental and ecological factors and processes naturally occur. However, ongoing changes are outside the normal range of variability;
- Changing weather conditions are most noticeable in the periods of spring break up and fall freeze up;
- Spring break up is happening earlier and more quickly;
- Fall freeze up is happening later and more slowly, often with abnormal freeze-thaw cycles;
- Longer ice-free season;
- Loss of permafrost; and
- Unpredictable changes in timing of fish movements.

Some changes observed on St. Lawrence Is. (Noongwook *et al.* 2007):

- Savoonga respondents reported the occurrence of new songbirds, ones without Alaska Native names.
- The timing of the spring migration of bowhead whales has advanced from April–May to March in response to changes in ice conditions.
- The migration is also less predictable because of changing weather and ice conditions.
- In recent years, Savoonga whalers have had to end their whaling season earlier because of deteriorating snow conditions in their return travel to the village.
- Unfavorable hunting conditions have affected Gambell spring whaling.
- The presence of bowhead whales close to St. Lawrence Island in winter has been associated with the reduction of multiyear ice. Harvests in late fall and winter have been

reported since the 1990s. In 1995–2005, about 40% of the whales harvested at St. Lawrence Is. were taken in winter rather than in spring.

Some changes reported by St. Paul, St. George, Adak, Atka and Togiak in the eastern Bering Sea (Huntington *et al*. 2013, Fall *et al*. 2013):

- Recent summers have been rainier than usual, making it difficult to dry fish.
- Increase in the occurrence of windy days; windy conditions in September have negatively affected harvest of bearded seals.
- Residents of St. Paul reported reduced abundance of fur seal with possible causes being predation by orcas and decline in the prey base due to ecosystem changes and competition with commercial fisheries.
- Togiak, just outside the ABSI-LCC, reported concerns about reduced abundance of a number of species important to subsistence, attributed to commercial fishing of herring (an important food source for many species), and habitat impacts of bottom trawling (specifically on clam beds on which walrus rely on). The most visible indicator of climate change with extensive ecological implications in this area is that sea ice is thinner, and the ocean freezes later in fall and melts earlier and quicker in spring.
- Changes in the Central and western Aleutian Islands are expected to be more like those reported for this region than for the eastern Aleutian Islands.

Environmental changes potentially related to climate change reported in eastern Aleutian communities (Reedy-Maschner and Maschner 2012):

- More seaweeds piled on beach at Nelson Lagoon than in the past.
- Increased abundance of sea otters, and their impact on marine invertebrates, also removing subsistence resources (at Nelson Lagoon, Akutan).
- Increased abundance of jellyfish, which are nuisances because they get caught in fishing nets (at Nelson Lagoon).
- Increase abundance of flounders, which is seen as a nuisance by salmon fishers (at Nelson Lagoon).
- Increased abundance of octopus and Atka mackerel (at Akutan).
- Increased abundance of eagles (at Akutan).
- Increased abundance of seals at Port Heiden. The Bristol Bay Native Association conducted a multi-year study of TEK and seals.
- Occurrence of "weird bugs" presumably due to temperature warming.
- Increased abundance of salmon sharks.

Importance of Cultural Resources for Sustainability of Subsistence Communities

"*How will we know it is us without our past*?" The Grapes of Wrath, John Steinbeck

Cultural resources are tangible material artifacts and intangible concepts pertaining to prehistoric, historic, and contemporary human cultures. Cultural resources are repositories of millenia of ecological knowledge and information regarding environmental change and processes. Tangible resources include settlements, deposits, structures, ruins, sites, buildings, graves, landscape features, and artifacts. Cultural intangibles are present in language, songs, stories, worldviews, place names, and belief systems. People and culture are intimately linked through time to landscapes and the wildlife and plants surrounding them. The essences of specific, though changing cultures, are as diverse as the people who made them and may emanate from physical, mental, or spiritual sources.

Cultural resources are voucher specimens of history and cultures. Cultural sites hold multiple layers of information about the lives of our ancestors. Without tangible places, we lose their stories, as if the people who came before never existed. Cultural sites maintain, both physically and symbolically, a sense of history and cultural continuity.

As repositories and archives, cultural resources (especially archaeological sites) contain stores of information on environmental conditions and processes usually not available anywhere else. Cultural resources document human societies, changes, and processes of innovation and adaptation to the ever changing physical and cultural world. For these reasons, it is very important to study and to protect cultural sites.

Resources and Services Most Likely to Be Affected by Climate Change

a. Vulnerable Biological Resources Important for Subsistence and Economic Activities

The ability to harvest and gather is a central point in Alaska's subsistence communities. Harvesting and gathering resources on the land determines peoples' feelings about themselves, structures their social relations, contributes to well-being, and provides a framework for relating with their environment (Callaway 1999). For these reasons, the possibility of loss, reduced availability, or reduced access to subsistence resources are a main source of concern for subsistence communities.

- Ice-dependent marine mammals (walrus, polar bear, ringed, spotted, bearded, and ribbon seals) are important subsistence resources and represent large proportions of harvests in some communities.
- Appropriate ice cover allows access to resources such as some fish and crab during winter, when other resources are usually scarce.
- Species that are important subsistence and commercial fishing resources may have their timing, abundance, or distribution affected by climate change. Future studies may specifically identify resources in this category.
- Some commercial fishing species (salmon, halibut, crabs) are important for the sustainability of rural communities. An evaluation of commercial fisheries landing data may allow identification of the most relevant species and interactions with other local activities. Besides the economical relevance of local fisheries, removals from commercial fisheries are also used for household consumption.

b. Vulnerable Habitats

- Sea ice,
- Areas subjected to coastal erosion and riverbank erosion,
- Areas subjected to floods by storm events, rising sea level, changes in rain patterns and freshwater dynamics,
- Loss of permafrost,
- Changes in vegetation cover and composition of plant communities,
- Changes in water circulation pattern due to changes in ice cover and increased fresh water runoff,
- With species moving northward due to climate change, bottom habitat critical for benthic species and species that depend on them is vulnerable to expanding fisheries.

c. Vulnerable Cultural and Socio-Economic Resources

- Cultural, historical, and archeological sites and cemeteries,
- Cultural diversity,
- Social stability,
- Economic viability,
- Infrastructure subject to erosion and floods.

Processes Affecting Vulnerability of Resources, Habitats, and Services to Climate change

a. Changes in Abundance and Distribution of Subsistence and Commercial Fisheries Resources

Changes in abundance and distribution of species may affect access and harvest success (food security) and lead to changes in fishing and hunting regulations (vessel size, net mesh size, number of hooks, size of harvest, and allowable species). Previously formulated hypotheses relating effects of climate change on subsistence activities in the Bering Sea from the North Pacific Research Board state (Hypothesis 5b): “climate-ocean conditions will change and thus affect the abundance and distribution of commercial and subsistence fisheries. For subsistence users, these changes will lead to: 1) greater reliance on owners of larger vessels that can travel farther to harvest and distribute subsistence goods, 2) decreased consumption of species with decreased local abundance and 3) adoption of new species into the diet as these species colonize local areas" (NPRB 2012).

b. Changes in the Distribution and Prevalence of Pathogens

Climate change may create opportunities for the dispersion and establishment of new pathogens in the ABSI region, causing diseases in people, animals, and plants. This process may happen thru the establishment of pathogens or vectors for diseases not currently found or rare in Alaska. Conditions that may influence the prevalence of pathogens include number of days above certain temperature thresholds, changes in temperature, and changes in precipitation (Bradley *et al*. 2005).

c. Unpredictable and Changing Weather, Wind, and Ice

(1) Changes in the climate, including wind and ice conditions, and general unpredictability in terms of weather, may affect access, harvest success, and safety of subsistence fishing and hunting and commercial fishing. Changes to weather, ice, polynyas, ice leads, and other environmental conditions may vary across the geographic region. (2) Spring and fall conditions are a main determinant of harvest opportunities because conditions may not be suitable for travel by boat or snow machine. More variable and unpredictable travel conditions because of ice, water level, or storms increase safety issues and the possibility of damage to equipment, with potential safety and financial hardships. (3) Increasingly unpredictable environmental (weather, ice) and ecological (animal migrations and behavior) conditions combined with time constraints imposed by wage employment narrows opportunities for harvesting and processing.

Changing and unpredictable environmental and ecological conditions affect traditional harvest and processing practices. Fishing nets have to be checked more frequently because warmer water temperatures affect the quality of the fish caught in the net. In warmer weather, flies and wasps appear earlier and negatively affect fish drying. Difficulties in properly drying or fermenting meat and fish can lead to spoiling. Some people have switched to freezing their fish and meat in electric freezers at increased costs, or to initially freeze their harvest and wait for favorable conditions for drying and fermenting. Changes in practices regarding the preparation and storage of wild foods have also lead to loss of knowledge regarding traditional methods.

In 2013 sea ice packed the shoreline of St. Lawrence Island preventing hunters from harvesting 2/3 of the walrus normally captured. The loss of the meat to feed families, and ivory for craft production, created very real hardships in a community with few alternative resources. The Governor declared the island an economic disaster area (Caldwell 2013). No State funds were made available for relief and religious groups stepped in to fill larders (Presbytery of Yukon 2013).

Socio-economic and cultural factors can also interfere with traditional harvesting, processing, and consumption patterns, and how people perceive the effects of environmental and ecological factors. In the past, when large amounts of fish and meat were necessary to feed dog teams, a few batches of fish unsuitable for human consumption were still appropriate to feed dogs. As dog teams have been replaced by snow machines, all harvests unsuitable for human consumption become unusable. This indirect process may have affected how people perceive environmental conditions leading to spoilage of harvests. This indirect process may have affected how people perceive environmental conditions leading to spoilage of harvests. Also, people may have less flexibility to time their harvests with favorable processing conditions because of wage employment.

d. Reduced Ice Cover

Some likely consequences and processes related to reduced ice cover include:

(1) Increased vessel traffic in northern oceans, will have many direct and indirect effects on rural communities;

(2) Increased contamination and chronic pollution related to increased vessel traffic will lead to issues related to food safety;

(3) Increased access to ice-free regions may favor development of other economic activities (e.g., oil and gas industry, commercial fisheries, tourism). On one hand, increased economic activities may bring more employment opportunities to rural communities. On the other hand, these activities may have negative effects such as increased competition for biological resources, changes to animal migration patterns, chronic and acute pollution, and potentially social conflicts.

(4) Reduced ice cover causes increased coastal erosion during storms.

e. Impact of Coastal Erosion and Flooding on Infrastructure

(1) Damage and destruction of infra-structure such as buildings, water facilities, sewage lagoons, landfills, and roads due to erosion and flooding cause economic hardship, disruption of daily life, and health issues. Erosion caused by storm surges has caused damage to infrastructure on Diomede (in the larger Aleutian-Bering Sea ecoregion) and likely in sites within the ABSI region.

(2) Coastal erosion also threatens cultural resources such as cemeteries, settlements, sites, buildings, and landscape features.

(3) Destabilization of relict military sites, exacerbating contamination issues and re-exposure of contaminated materials in sites that have had a superficial clean-up.

(4) Coastal and riverine camps, caches, drying racks and other infrastructure used for subsistence activities are being washed away across the Kawerak region due to storms and erosion.

f. Threats to Archeological Sites, Cemeteries, and Other Cultural Heritage Sites

Threats to cultural sites directly or indirectly related to climate change include:

(1) Reduced ice cover, rising sea levels, and increased frequency and severity of high water events may cause complete destruction of sites through erosion. Apart from complete loss, erosion-related damage to cultural sites include mixing of contexts, exposure of delicate artifacts leading to decay, crushing of artifacts, and exposure to looting. Some archeological sites in the ABSI region include human burials, increasing the concerns about the preservation these sites.

Damage to cultural sites leads to loss of scientific and cultural information contained within the sites.

(2) Exotic species (e.g., bison, cattle, muskox, reindeer, and sheep) have been historically introduced to many areas in Alaska, including the ABSI region, as a supplement to local resources or to replace local resources that have become less available. These introduced animals have caused extensive damage to cultural resources. Grazing of vegetation and trampling causes soil erosion, which may lead to destruction or damage of sites as explained above. New introductions of exotic species may be proposed to mitigate reduced availability of biological resources resulting from climate change.
(3) Looting of archeological sites can increase when people need supplementary sources of income. Direct and indirect economic costs of climate change may further increase the need of supplementary sources of income in the already economically stressed rural communities. Looting is defined as any digging for or removal of artifacts from archaeological sites when these activities are not authorized by the landowner. Looting is illegal on federal and state lands. Under Alaska state law, unauthorized digging is also illegal on private lands, but is unlikely to be enforced unless the landowner has policies against such activity. Recreational digging on federal or state lands is looting. Many Native corporation landowners are much concerned about unauthorized digging on their lands, but have few tools to prevent or stop it.
(4) Looting of archaeological sites is directly related to ease of access to sites. Changed climate related processes increase opportunity for access to sites. Looting has been reported when crews of fishing boats or canneries (e.g., Margaret Bay site in Unalaska) are idled by fishing closures, shortened seasons, or other reasons that may generate spare time. Loss of sea ice, shifts of economically valuable fisheries to the north, and the opening of Arctic shipping routes increases number of people moving into and through this region. Archaeological sites are likely more vulnerable to looting in summer when they are visible, accessible, and the ground is not frozen. As discussed above, climate change may affect fishing activities and fishing regulations. Looting by construction workers during development projects has been reported (e.g., Akutan airport, Shemya Island) and may increase as a consequence of climate change if construction projects are implemented to repair damaged infrastructure or to build new ones. As discussed above, climate change can cause damage and destruction of existing infrastructure, generate the need for alternative infrastructure, or to create the opportunity for new development projects.

g. Interactions with Economic and Demographic Processes, and Social and Cultural Well-Being

(1) Increased travel distances because of changes in weather, ice, and species abundance and distribution may reduce ability to afford continued participation in hunting and fishing and lead to safety concerns.

(2) Reduced productivity of commercial fisheries may affect sustainability of communities involved in those commercial fisheries.

(3) Loss of economic opportunity and of the subsistence base will further accelerate outmigration from communities as people seek better economic opportunities. A minimum population size is necessary to keep basic services such as a school, post-office, and regular flights.

(4) If communities are no longer sustainable, outmigration to larger urban centers will result in loss of cultural diversity.

(5) Increased commercial fishing and other economic opportunities may bring many newcomers that may destabilize subsistence cultures and social organizations.

(6) Demographic and socio-economic processes related to expansion or reduction of the population of communities may affect social and cultural sustainability. Progressive loss of cultural identity based on changes to the subsistence way of life may exacerbate social problems (dependence on assistance programs, substance abuse, violence, high suicide rates, etc).

(7) Alaska rural communities are already under strong economic stress. The per capita wage in general is very low. Therefore, all components of the total income (wages, dividend, retirement, public assistance) are important to meet needs, even if individual components are small (Callaway 1999:71). Although wages usually represent a large proportion of the total income, this component is subject to substantial variation, because many jobs are temporary. Many families are barely making ends meet and relatively small fluctuations in their income or expenses have a large effect on their ability to fulfill basic needs. Increased expenses resulting from climate change (erosion mitigation, longer hunting trips, reduced harvest success) increase the likelihood that families may not be able to fulfill their basic needs.

Exposure and Vulnerability to Climate Change

a. The northern and southern areas of the Bering Sea seem to be experiencing different patterns of physical changes with different consequences for the ecosystem. At the seasonal margin of sea ice extent, the Southern Bering Sea is more likely to see changes in the timing and extent of ice than the Northern Bering Sea, which maintains more consistent patterns of winter and spring sea ice. Northward expansion of species ranges, especially fish, are more likely to occur in the southern Bering Sea where differences in temperature and ice extent are greater between warm and cold years while the northern Bering Sea is expected to remain cold despite potential warming in the south (Stabeno *et al.* 2012). The occurrence, abundance, and distribution of ice-related marine mammals in the southern Bering Sea and their availability as subsistence resources may be negatively affected. For instance, the community of Togiak, in the Eastern Bering Sea has reported much decreased abundance of ice seals (Fall *et al.* 2013, Huntington *et al.* 2013).
b. Changing weather conditions have been most noticeable in the periods of spring break up and fall freeze up. Generally, spring break up is happening earlier and more quickly and fall freeze up is happening later and more slowly, often with abnormal freeze-thaw cycles. Subsistence activities specifically carried out during these periods may be more vulnerable to climate change (e.g., Raymond Yakoubian 2013). Variability and unpredictability are hallmarks of current weather patterns.
c. Archeological and cultural sites may be more vulnerable to erosion in stormy periods coinciding with open water (fall in Northern Bering Sea, fall and winter in Southern Bering Sea).
d. People have less opportunity to harvest and to properly time their subsistence activities because of time constraints imposed by wage employment. This makes it difficult to cope

with variability and unpredictability of resource abundance and access due to climate change.

e. Wage employment and financial challenges limits the amount of time some families spend together in subsistence pursuits and therefore may limit the transfer and acquisition of local and traditional knowledge. On the other hand, changing and more unpredictable ecological conditions require different knowledge to cope with variability and uncertainly in factors affecting travelling, harvesting, and processing of resources.

f. Financial challenges and high prices of harvest equipment and supplies constrain the capacity of rural residents to respond to changing ecological conditions. For instance, if walrus are migrating further from communities, it takes harvesters more gas, time, and (possibly) larger boats to access hunting grounds, all of these factors increasing costs of the activity. Also, traveling further from communities is more dangerous for hunters. Therefore, walrus hunting may become feasible for less hunters. Similar issues have been reported in the marine mammal harvests on the North Slope (Callaway 1995:60).

g. Increasing vessel traffic through the Bering Strait and northern Bering Sea is perceived as a major threat to marine mammals and subsistence communities. Vessel traffic has the potential to disrupt marine mammal migrations and to interfere with subsistence hunting (Raymond-Yakoubian *et al.* 2014, Kawerak 2013b, Kawerak 2015).

Adaptive Capacity

Some Documented Ongoing Adaptations:

a. More people rely on electric freezers to preserve their harvests and traditional processing methods are less used (drying, aging, fermenting, permafrost ice cellars) (Moerlein 2012, J. Raymond-Yakoubian 2013, B. Raymond-Yakoubian *et al.* 2014).

b. When other constraints allow (wage employment, equipment, water level), people try to get to camps and other harvest locations earlier so they do not miss earlier fish runs and other animal movements. Some people try to get to camps and other harvest locations earlier so they do not miss earlier fish runs and other animal movements. Some people are shifting their focus to alternate subsistence resources or activities, abandoning some fish runs, and focusing on other fish or other subsistence activities (e.g. Teller, on the Seward Peninsula, (Raymond-Yakoubian 2013).

c. In Akutan, hunters and fishers that own larger boats face increasing fuel costs and have tried to find efficiencies by fishing locally, limiting search time, and removing resources and incidental harvests from commercial fisheries rather than making subsistence harvest trips (Fall *et al.* 2013).

d. Communities readily take advantage of harvest opportunities resulting from changes in the environment and ecological conditions. For instance, a fall whaling season has developed in Savoonga in response to delayed freeze-up (Noongwook *et al.* 2007).

e. Increased reliance on readily accessible subsistence resources in an effort to lower grocery bills (Reedy-Maschner and Maschner 2012).

f. Social networks for production and sharing of resources are changing in response to variation in resource abundance and distribution. Some communities and individuals report less sharing due to increased costs and risks to obtain subsistence resources.

Case Study: Past Responses to Change on St. Lawrence Island and the Pribilof Islands

Aleut residents of the Pribilof Islands and St. Lawrence Island Yupik residents of St. Lawrence Island have experienced many major changes in the past two centuries. These include social change from increased interactions with persons from other places, economic change from modernization, competition in whaling and fishing, ecological change from cyclical regimes and recent warming, political change from ANCSA, and more. Although changes may bring disruption and turmoil, individuals and communities have displayed considerable resilience, which may shed light on possible responses to future change.

The following text is a brief overview of some of the major changes that have occurred since the 1870s on St. Lawrence Island (based on Bockstoce 1986, Noongwook *et al.* 2007, and personal communications from local residents) and since the 1980s on the Pribilof Islands (based on Huntington *et al.* 2009 and Fall *et al.* 2013). This exercise attempts to assess characteristics of changes and their relation to climatic, ecological, and socio-economic factors. It may help generate a better understanding of how past experiences relate to the types of changes expected in the coming decades. Although the changes discussed here are not all or solely related to climate change, the objective was to gain insight on how communities deal with change, whatever the underlying cause. This exercise also recognizes that the effects of climate change do not happen in isolation, but rather in interaction with ongoing, rapid socio-economic and cultural changes.

Pribilof Islands

The Pribilof Islands have been permanently occupied since the late 1700s, when Russian fur traders forcibly brought Aleuts there to harvest northern fur seals. The commercial fur trade lasted until 1984, when the United States' withdrawal from the Fur Seal Treaty put an end to commercial seal hunting, which had already shown signs of decline, especially on St. George. This event effectively removed northern fur seals as an economic resource, though subsistence use of fur seals continues at a modest level.

The sudden removal of a major prey species is a large shock to a social-ecological system. To help in the transition, some $20 million in grants were obtained by the communities of Saint Paul and Saint George to promote the development of commercial fisheries, including catching and processing. Commercial fisheries have been a variable success. Snow crab were abundant in the 1990s, leading to an increase in the human population on St. Paul, which declined after the crab harvests crashed around 2000. It seems this population increase was predominantly composed of young, non-Native males who moved to St. Paul during the economic boom, and left once the opportunity was gone. The loss of another major prey species again affected the social-ecological system, though the local Aleut population appears to have been relatively resilient to the change, at least in terms of total number of island residents.

Commercial fisheries continue today, though the economies of both communities have expanded to related areas such as harbor facilities (St. George especially) and contracts with the federal government (St. Paul especially). Grants for capital improvement projects, such as a new runway or road, provide temporary employment. Income levels in both communities have been high compared with other small, remote fisheries-oriented villages in Alaska, though incomes have also been highly variable. Population level does not appear to track income, suggesting a disconnect between economics and demography.

With the exception of the snow crab boom and bust, changes in the economic role of commercial fisheries in the Pribilof Islands appear to have been largely driven by regulatory and other change, rather than by ecosystem change. Requirements about where fish may be processed or the allocation of harvests among various users affect the economic attractiveness of the Pribilof Islands as ports, sites for fish processing, and bases for fishing operations. Nonetheless, such changes may be useful proxies for the loss of prey species, because the immediate effect is largely the same: loss of opportunity to use the resource.

Subsistence harvests also appear to be decreasing, likely as a result of changes in taste and preference, rather than in response to ecosystem change. The harvest of fur seals on St. Paul declined during the first decade of the 2000s, a period in which the fur seal population also declined sharply. However, the decline in fur seal harvest seems to be unrelated to availability, because far more fur seals come ashore on the island than are harvested. Requests for fur seals from tribal harvesters have declined, suggesting a lack of demand rather than a limitation of supply. If this trend continues, the impact of ecosystem shifts on the local communities may be lessened because of a weaker connection between people and the local ecosystem.

In summary, the Pribilof communities have experienced major shifts in economic opportunity and, in the case of the snow crab crash, ecosystem productivity of commercially desirable species. The communities have persisted through these changes, though perhaps with some degree of privation. Community and regional leaders have worked hard to obtain grants and contracts for the transition to commercial fisheries in the 1980s and various capital improvement and other projects in the 1990s and 2000s. Considerable hard work has contributed to the resilience both communities have displayed. Looking to the future, we can see that major shifts in the environment—or one's access to resources as a result of political or regulatory action—lead to major economic and social re-organizations. So far, these re-organizations have blunted the negative effects of the loss of major ecosystem services. However, further studies are necessary to assess the well-being and quality of life in communities that have endured such changes and to better understand the conditions that make successful re-organization possible.

St. Lawrence Island

St. Lawrence Island has been inhabited for millennia, and there are many archeological sites around the island. Its location is well suited for hunting marine mammals, as it lies across the migration routes of bowhead whales and walrus, and it is at the northern extent of subarctic species such as the Steller's sea lion. As many as five separate villages existed in the mid-19th century. At that time, commercial whaling for bowhead whales began, leading to regular contact between Native peoples of the northern Bering Sea and peoples of European and other descent involved in whaling. Trade provided goods such as metals and firearms to local people, but also brought disease and alcohol, which ravaged Native populations throughout the Americas.

The success of the commercial whaling greatly reduced the bowhead whale population and commercial whalers also pursued walrus, leading to a great decline in the walrus population. The combined reduction of availability of the two species most used by local people for subsistence culminated in a major famine in the winters of 1878-1880. Communities in the Russian mainland were affected as well, but St. Lawrence Island was particularly hard hit. About 1,000 lives were lost and only the community at Gambell remained. Savoonga was established in 1912 as a reindeer camp, and gradually grew to become its own community, now about equal in population to Gambell.

The loss of two major subsistence species, coupled with a lack of alternatives or outside support, led to this disaster. If such an event occurred today, humanitarian relief and other such interventions would reduce or prevent the loss of life as illustrated by relief efforts for St. Lawrence Island in 2013 (Presbytery of Yukon 2013). No famine occurred because island leaders could apply for state and federal aid, charitable organizations provided food and there are meal programs at schools and through other organizations.

In a more positive light, another adaptation to environmental change has occurred in Savoonga over the past two decades. Climate change has greatly altered the timing and characteristics of sea ice in the northern Bering Sea, so that freeze-up occurs later than it used to, and multi-year ice rarely drifts south through the Bering Strait. Also, unfavorable weather in spring has hampered whaling and walrus hunting, and rapid break-up and melt of ice in spring has reduced the duration of the walrus hunt. However, changes occurring in fall have produced a new opportunity to hunt bowhead whales in November and December. Since the early 1990s, about 30% of whales harvested by Savoonga have been taken in fall, representing an entirely new activity at that time of year. Had there been regulatory restrictions about hunting seasons, Savoonga would not have had the flexibility to adjust to this unpredicted opportunity in the midst of what are often perceived as unilaterally negative impacts from climate change.

In ecological terms, the favorable location of St. Lawrence Island means high productivity in most years, but poor weather conditions can prevent access to resources and thus lead to shortages of food. The fact that subarctic marine mammals already come as far north as St. Lawrence Island suggests that shifts in the distribution of marine mammals might bring new opportunities while others are lost. This is not to say that such shifts would, on balance, be positive or negative, just that there are offsets to consider rather than solely the loss of one set of opportunities.

Conclusions

On the Pribilof and St. Lawrence islands, past changes have often been met with innovation and adjustment. There are of course limits to how well individuals and communities can adapt. The St. Lawrence Island famine is an extreme example of how severe the effects of changes in abundance of key food species can be. On the other hand, the diversification of the Pribilof Islands economies, the new fall whaling in Savoonga, and other adaptations display a considerable capacity for innovation and resilience. Nonetheless, if reductions persist the cultural impact of reduced harvests can be substantial. For example, in the wake of the *Exxon Valdez* oil spill, many communities in the Gulf of Alaska and Aleutian Islands experienced lost or greatly reduced harvests of harbor seals and other resources, with the result that there were few or no opportunities for boys to learn the necessary skills for hunting, and for girls to learn how to process and care for the meat and organs. Such disruptions of knowledge transfer may have permanent consequences on social and cultural systems.

Changes of all kinds have occurred in the Bering Sea region over the past century or more, and are likely to continue for the foreseeable future. The immediate effects of many of these changes appear to be negative, as familiar ecological patterns are altered and the ways people gain livelihoods and well-being appear to be reduced. However, the extrapolation of current trends onto future conditions does not account for unforeseen changes in conditions that may occur and it is difficult to account for many involved factors. It is difficult to forecast innovation, and it is dangerous to simply assume that innovation will occur. Nonetheless, assessments of the implications of future change should also acknowledge that individual and community responses may well be adaptive across a wide range of conditions, and that disturbance need not lead inevitably to disruption and loss. Further development of this assessment should include case studies of abandoned communities that failed to cope with changes in an effort to further clarify key factors and processes involved in community resiliency.

Relevant Available Information to Assess Climate Change Vulnerability

While an extensive data compilation and analysis was beyond the scope of this assessment, it was relevant to identify some available data that could be integrated with outputs of climate models to identify the most vulnerable components and to prioritize mitigation actions.

a. Subsistence Harvest

- Traditional knowledge studies and other information is available from regional organizations such as Kawerak, Inc. Subsistence Resources and Social Science Programs (e.g., Ahmasuk and Trigg 2008, Tahbone and Trigg 2011, Gadamus 2013, Raymond-Yakoubian 2013, Kawerak 2013a, 2013c, 2013d, B. Raymond-Yakoubian *et al.* 2014, Kawerak 2013a, 2013c, 2013d).
- Comprehensive or resource specific household harvest surveys: conducted in selected years and communities surveyed by the ADF&G Division of Subsistence and other research bodies. The Community Subsistence Information System (CSIS) compiles information generated by the ADF&G Division of Subsistence and other compatible studies (http://www.adfg.alaska.gov/sb/CSIS/). Other information is available as project reports produced by organizations such as Kawerak, Inc. Subsistence Resources and Social Science programs (e.g., Ahmasuk and Trigg 2008, Tahbone and Trigg 2011,

Raymond-Yakoubian 2013, Kawerak 2013a, 2013c, 2013d, B. Raymond-Yakoubian *et al.* 2014, Kawerak 2013a, 2013c, 2013d).

- Harbor seals and Steller sea lion: annual harvest monitoring program conducted by the Alaska Native Harbor Seal Commission (ANHSC) and ADF&G Division of Subsistence (1995–2008, covered about 60 communities, including all communities of the Aleutian-Bering Sea Islands). Information available online at the CSIS and as annual reports.
- Birds and eggs: harvest monitoring program of the Alaska Migratory Birds Co-Management Council (AMBCC), better annual coverage for Gambell and Savoonga (data available at village level only for these villages, at regional and subregional level for other areas), poor coverage of Aleutian and Pribilof Islands.
- Halibut: NOAA-NMFS subsistence halibut harvest monitoring implemented by ADF&G Division of Subsistence (2003–2012, villages). Data available as annual reports.
- Walrus: Eskimo Walrus Commission and USFWS marine mammal marking, tagging, and reporting program (1989–present) http://www.fws.gov/alaska/shellfish/mmm/mtrp/pdf/factsheets/stats_walrus.pdf

  Alaska Department of Fish and Game, Village-based Walrus Habitat Use Studies in the Chukchi Sea. http://www.adfg.alaska.gov/index.cfm?adfg=marinemammalprogram.walrustracking
- Polar bear: marine mammal marking, tagging, and reporting program conducted by USFWS (1987–present) http://www.fws.gov/alaska/shellfish/mmm/mtrp/pdf/factsheets/stats_pbear.pdf
- Sea otter: marine mammal marking, tagging, and reporting program conducted by USFWS (1989–present) http://www.fws.gov/alaska/shellfish/mmm/mtrp/pdf/factsheets/stats_sea_otter.pdf
- Ice seals (ribbon, spotted, bearded, and spotted seals): limited harvest monitoring conducted by ADF&G Division of Wildlife Conservation (Mark Nelson) in collaboration with the Ice Seal Committee (2006–present).
- Bowhead whale: annual harvest reports produced on behalf of the Alaska Eskimo Whaling Commission.
- Beluga: Alaska Beluga Whale Committee (for further information contact Robert Suydam, Lori Quakenbush).

b. Commercial Fisheries Data Relevant for Subsistence Systems

- ADF&G Subsistence Reports at http://www.adfg.alaska.gov/index.cfm?adfg=subsistence.harvest
- Commercial Fisheries Regulations at http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyareanortonsound.main http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyareaaleutianislands.main
- Fish Count Database at http://www.adfg.alaska.gov/sf/FishCounts/
- Information on each Fishery http://www.adfg.alaska.gov/index.cfm?adfg=fishingCommercialByFishery.main

c. Demographic and Economic
Local governments, Native corporations, regional non-profits, and other organizations have developed economic and development plans for individual communities (e.g., for Diomede http://www.kawerak.org/ledps/diomede.pdf). These plans describe the socio-economic setting; identify infrastructure, social, and economic needs; and propose mitigation actions including issues related to climate change (e.g., erosion). Information is also available from the Alaska Department of Community, Commerce, and Economic Development (DCCED).

d. Cultural Heritage
The Alaska Heritage Resources Survey (AHRS) is a statewide inventory of cultural properties maintained by the Alaska Office of History and Archaeology (OHA). The information on this database is limited to that provided by individuals to the OHA and coverage is uneven. The data refers to tangible remains such as archaeological sites, old settlements, structures, ruins, buildings, graves, and artifacts. Less tangible culturally important areas such as landscape features and sites with few visible remains are absent from the inventory. Local residents, tribal entities, Native social and cultural service organizations such as Kawerak Inc., Native Corporation landowners, and government land managers possess other sources of relevant information.

e. Weather and Other Environmental and Ecological Factors
(1) In some villages, interested individuals have been keeping periodic observations (daily, weekly) on environmental and ecological factors for years or decades (e.g., Nelson Lagoon; Reedy-Maschner and Maschner 2012). Researchers could seek partnership with these individuals to develop the potential of these data sources, integrate other sources of information, and make the information available for the local people and larger public. These collaborations have the potential to develop research capacity within communities while recognizing local partners as primary research authors.
(2) Relationships between marine mammals and ice are very specific and involve different ecological factors and conditions necessary to meet animals' needs. For instance, walrus depend on sea ice strong enough to support their weight, furthermore this kind of ice needs to be over water shallow enough to allow walrus to reach the sea bottom to feed. Local and traditional knowledge includes a wealth of information on how marine mammals relate to and depend on sea ice (Gibson and Schullinger 1998, Callaway 1999:67, Kawerak 2013d). Specific collaborative projects designed to document and compile this knowledge may help understanding effects of loss and changes to sea ice on marine mammals and to people dependent on them.

Recommendations

Information Gaps

1. Fine-resolution information on variation of sea level and local topography may help assess vulnerability of coastal cultural and archeological sites.
2. Change and variation in ice condition (extent, thickness, age, kind of ice).
3. Variation in conditions affecting occurrence and distribution of polynyas and ice leads, what affects distribution of birds and marine mammals.

4. Variability in strength and volume of inter-island currents, upwellings, and coastal currents.
5. Variation and change in range distribution and seasonal timing of species. From a subsistence perspective, definitions of seasons are variable depending on resources, location, and annual variations of climate and ecological processes.
6. Indicators of storminess.
7. Affects of cold pool changes on subsistence systems.
8. Develop better understanding of how climate change interacts with other ongoing socio-economic and cultural processes affecting life in rural Alaska.
9. Support applied approaches to integrate TEK into research, management, and policy development.
10. Conduct ethnographic research to understand past and current adaptive responses by local communities to ecological and socio-economic drivers of change.
11. Increase community awareness of potential changes and necessary preventive and mitigation actions to respond and adapt to increasing vessel traffic in Bering Sea.

Mitigation Actions

The socio-economic and cultural settings of Alaska Native Villages are complex and interact in many ways with environmental and ecological changes. Therefore, it is difficult to isolate drivers of change and forecast directions of change and adaptive responses by communities. Nevertheless, consequences of climate change are yet another stressor in Alaska rural communities. Given many uncertainties, climate change mitigation actions derived from optimal strategies that maximize benefits while minimizing costs and negative consequences have the best potential to promote the long-term sustainability of subsistence cultures and communities. Such optimal strategies yield benefits to communities even if climate is eventually not a main driver of change.

Cultural Sites

1. Develop a comprehensive inventory of historic, cultural, and archeological sites, including information on topography, geology, and identified threats (erosion, flooding, trampling, and looting). Involve communities in this process.
2. Document (excavation, research) and protect (stabilize) threatened sites based on priorities defined by local communities and researchers.

Harvests

1. Identify alternative subsistence and commercial resources that are sustainable in the short and medium term.
2. Assess needed changes to harvest regulations to allow sustainable harvest opportunities given changing timing and abundance of resources.
3. Design and implement food safety monitoring program to assess levels of contamination in subsistence and commercial harvests, which may result from increased vessel traffic and other economic activities.

4. Develop measures to limit and direct vessel traffic during certain times of the year to protect subsistence resources, harvesters, and harvest activities.
5. Support local participation and the inclusion of local and traditional knowledge in resource management (co-management bodies, regional advisory councils) and policy development.

Socio-Economic Well-Being

1. Develop and improve multi-agency coordination to detect and respond to sources of contamination related to increased vessel traffic and other economic activities (e.g., chronic and acute oil spills).
2. Communities affected by coastal erosion may need mitigation actions including relocation. Develop sustainable economic and cultural approaches to identify new sites and implement relocation, considering issues of access in and out of the community, geology, and access to subsistence resources.
3. Develop and refine approaches to communicate climate research results including model output scenarios and vulnerability assessment with rural communities (language, time and spatial scale). The need for better communication has been identified in previous assessments (Cohen 1997, Callaway 1995:62).
4. Work with communities to develop approaches to prevent and reverse outmigration that may cause communities to disappear (development of local economic opportunities, support education, financial assistance with changing equipment needs, training in using new technology, licensing, permitting).
5. Support and promote cultural heritage activities, participation of youth in subsistence activities, programs to preserve and recover proficiency in Native languages.
6. Directly involve communities in climate related research. One approach to achieve this objective is to develop and support environmental community-based monitoring programs incorporating western science and local and traditional knowledge (Callaway 1999:62).

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Chapter 5: Climate Vulnerabilities for Marine Mammals

Carole Fairfield, Verena Gill, James MacCracken, Lori Polasek, Andrew Trites and James Valade

Introduction

We considered the potential effects of climate change on the approximately 20 species of marine mammals known from the ABSI region (Allen and Angliss 2013). We identified four species and two taxonomic groups of greatest concern. These species/groups were prioritized for consideration based on 1) documented or theorized risk from climate change; 2) existing management concern about conservation status; 3) other documented threats to species viability or habitat and 4) the importance of the species or group to stakeholders in the region. We identified several pinniped species in the ABSI region including walruses, Steller sea lions, northern fur seals, and a group often referred to as "ice seals" that includes bearded, spotted, ringed and ribbon seals. We also considered sea otters and whales.

Across these species and groups we identified broad concerns relative to climate change and ocean acidification having impacts on prey species that would then cascade up as indirect impact to these higher trophic level predators. With respect to walrus and ice seals the physical loss of sea ice and snow result in direct effects resulting from climate change. Additionally increase storminess may have direct impacts to pups on rookeries for Steller sea lions and fur seals as well as young sea otters. Other environmental stressors we considered relate to climate-connected effects of increase vessel traffic through the ABSI region as a result of a longer ice-free season.

What follows is an evaluation of threats faced by each of these species and one species group, with an assessment of the specific vulnerabilities associated with changes in climate as well as related threats. We assess the adaptive capacity of each species or group and close with recommendations for key research needed to address these climate vulnerabilities.

Ice Seals

There are four species of ice seals: spotted, ringed, ribbon and bearded seals. All will be impacted by ice loss. Within this group we focus primarily on ringed and bearded seals because of their documented conservation concerns as evidenced by recent consideration under the Endangered Species Act. Bearded seals live on sea ice during critical months for breeding, pupping, nursing and molting. Ringed seals use sea ice for molting and build snow caves on top of sea ice to shield their pups from freezing temperatures and predators (Smith and Stirling 1975). Both species are also thought to be vulnerable to potential impacts from increased vessel traffic in the Arctic and from oil and gas development activities (Laidre *et al.* 2015).

No special management zones have been established for bearded seals but in December of 2014 National Oceanic and Atmospheric Administration (NOAA) proposed designating a vast area of 906,000 km2 in the northern Bering as well as Chuckchi and Beaufort seas (NOAA 2014). It is speculated that changes in the climate will lead to shifts in animal ranges and therefore increased potential exposure to novel diseases. Documentation of current disease loads and an understanding of the effect of those diseases are needed. Although there has not been any documented impact to date, ocean acidification has the potential to impact prey resources directly for bearded seals or indirectly (thought prey shifts) in ringed seals.

Many villages in Alaska rely on ice seals for subsistence. Within the ABSI region the following villages consume bearded and/or ringed seals: Point Hope, Diomede, Gambell, Savoonga, and Hooper Bay. Declines in seal numbers or condition could greatly impact food security, as well as the positive impacts that the harvest, consumption and associated activities have on social and cultural well-being. Other villages will likely also be impacted, but those listed have the highest (best documented) take in the ABSI LCC region.

Northern fur seals

Northern fur seals on the Pribilof Islands have declined by over 80% since the 1970s and were listed as depleted in 1988 under the MMPA. There is significant concern about their conservation status given that the cause of the decline is unknown (NMFS 2007). One possible explanation for the population decline on the Pribilof Islands is a shortage of prey species available to lactating females in the Bering Sea during summer and fall. Climate change is predicted to alter the distribution and abundance of prey species in the Bering Sea (Mueter and Litzow 2008; Hunt *et al.* 2011; Mueter *et al.* 2011), which may further impact the ability of northern fur seals to feed themselves and adequately nourish their pups.

Newborns are the most vulnerable portion of the northern fur seal population, and are likely to be the age group most affected by climate change. The biggest impact is likely to come from extreme weather events from July to October that increase the numbers of young and malnourished pups dying from hyperthermia or drowning (Trites 1990; Trites and Antonelis 1994; Spraker and Lander 2010). Rising sea levels and increases in the frequency and intensity of storms (wind speeds and wave conditions) are also likely to alter the availability of resting (haulout) and breeding (rookery) sites used on St. Paul, St George and Bogoslof Islands, which may in turn negatively affect fur seal numbers.

There are no protected areas for northern fur seals in the Bering Sea (NMFS 2007), although fur seals may incur some indirect benefit from the fishing exclusion zones around nearby Steller sea lion rookeries on Bogoslof Island and Walrus Island (Pribilofs) (NMFS 2014a). Northern fur seals are a very important part of the cultural identify of Aleuts living on the Pribilof Island (NMFS 2005, 2014b). Subadult male fur seals are also an important part of the diets of some people living in the communities of St. Paul and St. George. Fishing (halibut) and seafood processing (halibut, crabs and snails) have also been important to the economies of these communities and may be negatively affected by climate-induced changes in the distribution and abundances of commercially important marine species.

Sea otters

Northern sea otters of the southwest Alaska stock range along the Alaska Peninsula and Bristol Bay coasts and the Aleutian, Barren, Kodiak, and Pribilof Islands. Otters are commonly found in near shore areas but can be observed offshore rafting. They tend to prefer kelp dominated habitat. Their winter range is restricted to those areas free of ice; ice-free areas are needed for foraging purposes. Otters primarily feed on invertebrate species, including echinoderms and shellfish.

Sea otters were removed from much of the region due to the fur trade that predominated well into the late 1800s. Absent from the landscape, nearshore ecosystems changed significantly and these environments became species poor; notably, kelp forests disappeared and mono-specific communities (i.e., urchin barrens) predominated. Resurgences in Alaskan sea otter populations have resulted in a return of kelp forests and healthy, diverse faunal communities.

Sea otters in the ABSI region are listed as threatened and critical habitat has been designated in this region. This stock grew in size for decades and then declined dramatically in the 1980s and 1990s. The cause of the decline remains unknown but the weight of evidence suggests that increased predation on sea otters, perhaps by orcas, is the most likely cause. Threats to sea otters in this region include predation, infectious diseases, biotoxins, food limitation, disturbance, loss of habitat, contaminants, oil spills, bycatch in fisheries, subsistence harvest, and illegal take.

These threats may be exacerbated by climate change. Redistributions in cetacean ranges due to changing temperatures may increase sea otter predation rates. Infectious diseases once constrained by extreme winter temperatures are now present and have been implicated in the deaths of sea otters. Ocean acidification will affect the invertebrates that make up the sea otters diet. Increases in available oil and shipping will increase the risk of oil spills known to affect sea otters.

Steller Sea Lion

Following a well-documented decline in abundance of more than 80% in the last 30 years, Steller sea lions (*Eumetopias jubatus*) were designated as “threatened” range-wide under the U.S. Endangered Species Act (ESA). Two distinct populations, a western and an eastern stock, were identified with the division at Cape Suckling, Alaska (144°W). Additional declines resulted in an “endangered” up-listing of the western stock, while eastern populations maintained the “threatened” designation.

Current research suggests that fecundity of western stock females has decreased to the extent that the stock has limited ability to recover (Holmes *et al.* 2007). It is widely accepted that nutritional and reproductive requirements affect fecundity to some extent, and that more studies in this area are vital to better understand these requirements. Concerns for population recovery have already led to critical habitat designation around Steller sea lion habitat (50 CFR

226.202). The western stock of sea lions is designated as endangered and critical habitat designation has led to fishing restriction.

Climate change will likely bring changes in the weather, water temperatures, and increased storm surges in the ABSI region. Pup loss due to storm surge is one of the highest causes of mortality in Steller sea lions pups (Maniscalco *et al.* 2008). It is postulated that storm surge, coupled with the potential shifts in prey with changing water temperature, could negatively impact population recovery. Summer rookeries with females nursing and foraging to support new born pups will be the most vulnerable to changes in prey and waves.

Walrus

For the Pacific walrus, the ABSI area is primarily a winter range (typically the 50 km wide ice edge and predictable polynyas) and contains 2 of 3 suspected breeding areas (SE of St. Lawrence Island and S of Nunivak Island). In general, ice projections out to 2099 indicate that ice will be available for overwintering and breeding in the Bering Sea (Douglas 2010, Wang and Overland 2015). Ice may melt out sooner and more rapidly in the spring, which may result in parturition farther north than in the past. Implications of that are unknown. In addition, the migration of females and young animals north to the Chukchi Sea will likely begin sooner in the spring and occur faster than in the past as thinner first year ice also melts faster.

Typically, most of the Bering Sea is ice-free by June or July and ice does not reform until November or December. The duration of the ice-free period in the Bering Sea is expected to increase in the future (Douglas 2010). As noted above, female walruses and young animals migrate to the north with the retreating ice edge. Most males remain in the Bering Sea year-round and use coastal haulouts to rest between feeding bouts in the summer (Fay 1982). Declines in seasonal sea ice cover in the Bering Sea may indirectly affect walruses due to changes in prey mass, species composition, and distribution as a result of increased water temperatures, changes in the bottom water cold pool, and ocean acidification (Jay *et al.* 2011, MacCracken 2012). Bering Sea waters have been warming and pH has been declining for decades and at an accelerated rate (Fietzke *et al.* 2015) and changes in the distribution of some benthic species has been noted (Lovvorn *et al.* 2009, Grebmeier 2012) but effects on walruses have yet to be detected. Walrus feeding activities (i.e., bioturbation) are thought to be important in nutrient cycling and benthic productivity (Ray *et al.* 2006).

The use of coastal haulouts by walruses in the region can be highly variable in terms of timing, duration of occupancy, and numbers of animals present (Jay and Hills 2005). Human disturbances and localized prey depletion may influence the use of specific sites. Recent changes in use from more southerly sites to haulouts further west and north may be a reflection of those factors as well as diminished winter sea ice extent.

The majority of walruses harvested for subsistence purposes in the United States are taken by hunters from St. Lawrence Island. Harvests have been steadily declining since 1990 due to several factors, but the most important may be the increased rate of ice melt, speed of the spring migration, and increased frequency of high winds and rough seas. Harvests in 2013 – 2015 were far below average and the State of Alaska declared a walrus subsistence harvest disaster in 2013.

Changes in sea ice dynamics may also result in increased economic activities in the Bering and Chukchi Seas. International shipping, commercial fisheries, oil and gas development, tourism, etc. all become more feasible as the ice-free season increases (Jay *et al.* 2011, MacCracken 2012). The Bering Sea and Bering Strait contain major shipping lanes for accessing the Chukchi Sea as well as the Northeast and Northwest Passages as they also become passable. With increased economic activities, the likelihood of an accident that releases crude oil, fuels, or other contaminants also increases.

Many of the potential stressors associated with the changes in sea ice dynamics have yet to materialize or notably affect walruses. We expect these stressors to increase in intensity in the future, but exact timelines and magnitude of effects are difficult to project. In addition, alternative scenarios are also plausible (MacCracken 2012).

Whales

Several species of sub-arctic cetaceans, including odontocetes and mysticetus, are being observed in areas not previously recorded, with the speculation that the change in distribution is due to climate change. Species recorded with more frequency in the ABSI LCC area than previous years include right, fin, and minke whales (Allen and Angliss 2013). Additional species already using this area (gray, bowhead, humpback, and killer whales) can be expected to respond to climate change, though to date it seems this is limited to the northward extension into the Chukchi and Beaufort Seas (Allen and Angliss 2013). Bowhead, gray and possibly killer and humpback whales may have adequate monitoring to explore species response to climate change, but this may be limited to showing changes in distribution.

There is a general lack of information about critical habitat needs of cetacean species in the ABSI region making conclusions about climate change effects difficult. However, there are a couple of key species with other related conservation threats or their vital role in subsistence harvest by communities that warrant additional consideration. Bowheads are an important species harvested by residents from Gambell and Savoonga on St. Lawerence as well as other communities in the region including Wales, Little Diomede, and Kivalina (2014 FR Notice Vol. 79 (42): 12184).

Oil and gas activities made more feasible in the Chukchi and Beaufort Seas as result of decrease summer sea ice, have been suggested as a potentially negative stressor with the possibility of affecting migration of bowheads through the Bering Strait. This could impact to individuals within the population as well as have implications for the communities that harvest this species.

One of the world's most endangered marine mammals, the North Pacific right whale, is found in very low numbers in the ABSI region. Before commercial whalers heavily exploited right whales in the North Pacific, concentrations were found in the Gulf of Alaska, eastern Aleutian Islands, south central Bering Sea, Sea of Okhotsk, and Sea of Japan (Braham and Rice 1984). Following commercial exploitation and illegal whaling in the 1960's, there were only 82 sightings of right whales in the entire eastern North Pacific, with the majority of these occurring in the Bering Sea and adjacent areas of the Aleutian Islands (Brownell *et al.* 2001).

Since 1996, scattered right whales have been consistently observed in Bristol Bay and the southeastern Bering Sea during the summer months. No calving grounds have been identified to date (Scarff 1986), and migratory patterns are unknown, although there is speculation that this population migrates from high-latitude feeding grounds in summer to more temperate waters during the winter, possibly well offshore (Braham and Rice 1984; Scarff 1986; Clapham *et al.* 2004).

In 2008, NMFS listed the endangered northern right whale **(***Eubalaena spp*.) as two separate, endangered species, the North Pacific right whale (*E. japonica*) and the North Atlantic right whale (*E. glacialis*). This required the designation of critical habitat for the North Pacific right whale. The same two areas within the Gulf of Alaska and within the Bering Sea, that were previously designated as critical habitat in 2006 for the northern right whale (NOAA 2006), are now designated as critical habitat for the North Pacific right whale (NOAA 2008). Studies begun in the early 2000's continue to identify areas where these whales forage throughout the summer, based on both visual observations as well as recordings of right whale vocalizations. Bottom-mounted acoustic recorders in the southeastern Bering Sea indicate that right whales remain in the southeastern Bering Sea from May through December with peak call detection in September (Mellinger *et al.* 2004; Munger and Hildebrand 2004; Stafford and Mellinger 2009). More recent recorders indicate the presence of right whales in the southeastern Bering Sea almost year-round, with a peak in August and a sharp decline in detections in early January (Catherine Berchok, pers. comm). Use of this habitat may intensify in mid-summer through early fall based on higher monthly and daily call detection rates.

The estimate of abundance for right whales in the Aleutian Islands and Bering Sea based on photographic and genotype data through 2008 is 28 (95% CL 24-42) and 31 (95% CL 23-54), respectively (Wade *et al.* 2011). Analyses of biopsy samples (LeDuc *et al.* 2012) indicate a male-biased sex ratio and loss of genetic diversity, putting this population "at extreme risk of extirpation". Ship strikes are significant sources of mortality for the North Atlantic stock of right whales, as it may be for the North Pacific population. Their scattered distribution and low numbers make it impossible to assess the threat of ship strikes given current data, though the effects of increased vessel traffic with retreating sea ice may increase the potential risk to right whales.

Key Climate Sensitivities & Exposure

We identified four drivers related to climate relative to potential expected effects across these species and groups. These were selected based on 1) relative certainty of climate relationship to known thresholds important to species or groups; 2) relative certainty of change in climate condition and 3) tractability of possible follow up research questions that can be recommended to leadership of ABSI LCC, the Alaska Climate Science Center and AOOS.

Changing Sea Ice Extent and Character

Whales – The timing and routes of both the spring and fall migration of bowheads has been tied to ice coverage and areas of open leads. Calving locations in the North Pacific remain unknown (Brownell *et al*. 2001; Clapham *et al*. 2004; Shelden *et al*. 2005). An increase in open water during the winter may result in a more northern extent for this species during the winter, which may also impact subsistence use. North Pacific right whales may also extend their winter range more northerly, though so little is known about this highly endangered species' wintering grounds, that it is impossible to predict ice impacts on this whale. The fin, minke and humpback whales which move to low latitude wintering and calving grounds might only be affected by ice loss during summer months, during which higher latitudes that become ice free would be accessible to these species, provided their food resources likewise move northerly in their range.

Walruses - Sea ice needs to be at least 60 cm thick to support walruses and we assume that walruses will track appropriate ice habitats as they change in location for breeding and parturition. Changes in sea ice coverage may result in changes in locations of breeding aggregations. A general northward shift in distribution appears to be occurring along with a decline in use of some Bristol Bay coastal haulouts. Parturition occurs on the ice and may occur further north. These changes will also require walrus hunters to modify their traditional hunting periods and locations in the spring and fall.

Bearded seals – This species needs sea ice for long durations including for breeding, pupping, nursing and molting from spring through to late fall. They use ice of varying conditions including thinner ice for hauling out and thicker, land fast ice for foraging and breathing holes (Burns 1981). Loss of ice for pupping has the potential to bring seals to land which would increase exposure to predators. It may also make the animals shift to unexpected areas both annually and seasonally making seals less accessible to hunters in traditional harvest areas. Similarly, given that hunts often occur on ice, loss of ice forces changes in traditional hunting practices.

Ringed seals – The loss of snow cover for pupping has the potential to heavily impact pup rearing success and vulnerability to bear predation. Ringed seals need 20 cm of snow for lairs during late spring and early summer (Smith and Stirling 1975). Similar to bearded seals, loss of sea ice may cause this species to shift to terrestrial habitats for denning and could make them more accessible to predators. Also like bearded seals, they may shift to unexpected areas annually or seasonally making them far less accessible to hunters. Finally, harvest often occurs on ice, which could further impact traditional harvest.

Sea otters - If sea ice is expected to decrease in seasonal extent sea otters could move into previously unavailable winter habitat. However, if these decreases in seasonal ice were accompanied by short-term cold weather extremes, sea otters in newly available habitat could be precluded from foraging by ice produced during extreme cold events.

Increased Storminess

Whales- Timing of bowhead harvest is already being affected in subsistence communities due to ice conditions (Suydam *et al.* 2011). High seas and more frequent storms make it increasingly difficult for shore based subsistence whalers to launch their small skiffs.

Northern fur seal - High winds and heavy rain can cause hyperthermia and kill newborn and malnourished northern fur seal pups (Trites 1990; Spraker and Lander 2010).

Sea otters - An increase in storm frequency during breeding pulses in late spring may increase sea otter pup mortality (Blood 1993).

Steller sea lions - Reproductive rates are poorly understood in the ABSI region. Pup loss due to storm events are one of the most frequent cause of pup mortality (Maniscaclo *et al.* 2008) and therefore increased events could have a high impact and wave action in the summer will have a high impact on rookeries with pups.

Trophic Disconnects for Key Prey Species

Walruses and bearded seals – There is a possible disruption of the links between primary production resulting in robust populations of benthic species favored by these species. For example, projections made by Hermann *et al.* (2013) suggest a northward shift in benthic biomass. A closer inspection of their projections shows declines in benthic biomass south of the Yukon/Kuskokwim Delta and south of St. Lawrence Island. Additionally these two species focus on prey species that are also expected to be vulnerable to the effects of ocean acidification.

Sea otter – Changing temperature thresholds in the water column could be an issue for sea otter prey. Otters need to be in shallow nearshore waters for feeding and breeding. They tend to inhabit waters <100m in depth (Riedman and Estes 1994), so if prey resources move deeper due to warming waters, it may reduce their availability to otters.

Steller sea lions – The primary prey of Steller sea lions in the Bering Sea are Walleye Pollock and Atka mackerel (Sinclair and Zeppelin 2002). Climate change has the potential to disrupt ecological linkages between trophic levels of the Bering Sea, which could reduce the availability and quantities of these dominant prey species, and negatively affect the breeding success of the fur seals. Any reductions in prey availability that extend the duration of feeding trips will reduce the amount of energy mothers can ultimately transfer to their pups. This in turn will reduce the probability of pups surviving after they are weaned. Pups in the Aleutian Islands can fast for an average of 9 to 25 hours while their mothers travel in search of food (Trites *et al.* 2006).

Northern fur seal - In the Bering Sea, northern fur seals primarily consume squid, northern smoothtongue, juvenile pollock, Pacific salmon, Pacific sand lance, Pacific herring and Atka mackerel (Sinclair *et al.* 1994; Sinclair *et al.* 2008; Call and Ream 2012). Climate change has the potential to disrupt ecological linkages between trophic levels of the Bering Sea, which could reduce the availability and quantities of these dominant prey species, and negatively affect the breeding success of the fur seals. Any reductions in prey availability that extend the duration of feeding trips will reduce the amount of energy mothers can ultimately transfer to their pups. This in turn will reduce the probability of pups surviving after they are weaned. Pups on the Pribilof Islands fast for about 7–8 days on average while their mothers travel about 600 km in search of food (Kuhn *et al.* 2010; Nordstrom *et al.* 2013).

Related Threats

Increased vessel traffic in the region as a result of longer periods of reduced sea ice will introduce many variables into a system already dealing with a changing climate. Potential impacts from shipping include: the release of oil through accidental or illegal discharge, ship strikes on marine mammals, the introduction of alien species, disruption of migratory patterns of marine mammals, and increased anthropogenic noise, atmospheric emission and disturbance (AMSA 2009).

The International Maritime Organization approved the adoption of the Polar Code in November 2014. The code contains a number of environmental protection measures that have been incorporated into the mandatory Convention for the Safety of Life at Sea and the International Convention for the Prevention of Pollution from Ships for vessels operating in the Arctic.

Ocean acidification is expected to impact marine invertebrates in Alaska. The Bering Sea has been documented as one of the world's mostly highly acidic regions (Takahashi *et al.* 2014). Acidification has been shown to impact invertebrates in both laboratory experiments and the ocean (e.g. Kurihara 2008; Seibel *et al.* 2008; Kroeker *et al.* 2010). Change in or loss of diversity or numbers of benthic invertebrates will likely impact marine mammals that rely heavily on them for prey such as walruses, bearded seals, and sea otters. Similarly, impacts to zooplankton could change the trophic dynamics of pelagic food webs as well—thus having potential implications for more marine mammal species.

Evaluating Adaptive Capacity

We evaluated adaptive capacity to these threats relative to each species or species group as well as how human communities dependent on them might also adapt. We considered inherent flexibility in the species themselves as well as possible management actions that could be taken to maximize potential for adaptation to climate change. We also considered complementary actions managers might be able to take to mitigate for the effects of climate change.

Walruses – The evolutionary history of walruses is long and complex with a wide variety of morphologies in the fossil record suggesting exploitation of a variety of marine environments and food resources (Boessenecker and Churchill 2013). This species generally tracks sea ice dynamics and are not rigidly tied to any specific location (Fay 1982). They prey on several invertebrate taxa and occasionally fish and seals suggesting some flexibility in diet (Sheffield and Grebmeier 1990). Males readily use coastal haulouts in the Bristol Bay region suggesting flexibility in habitat use (Fay 1982, Jay and Hills 2005). The majority of harvested walruses are taken by hunters from St Lawrence Island. Those hunters should be able to adapt to changes in walrus spring migrations (earlier and quicker) assuming the weather cooperates. High winds and waves resulting from reduced ice coverage and shore packed ice from persistent north winds have been obstacles to St. Lawrence Island hunters the last several years. However, increased hunting during the fall migration may be able to offset low spring harvests. Managers and communities can try to offset potential climate impacts by ensuring that walruses on coastal haulouts are not disturbed and by continuing to implement mitigation measures associated with resource development. Similarly, mitigation is needed to address risks from increased vessel traffic. Other considerations could be to limit fisheries that may impact walrus prey, and support for the practices of self-regulation of the harvest by hunters, and efforts to reduce hunting struck and lost rates.

Steller sea lions – Steller sea lions in the Aleutians have not shifted east where the population has been delisted. Therefore it is questionable if movement or adaptation to new rookery locations to follow shifts in prey species can be expected. As with other marine mammal species, protecting haulouts from disturbance is an important mitigation against other potential stressors from climate change.

Northern fur seals – This species and the people that depend on them seem unlikely to have much capacity to adapt to some of the changes projected to occur in the Bering Sea. Most notably, northern fur seals are central place foragers that are entirely dependent on the quality and quantity of prey surrounding their three breeding islands (NMFS 2007; Kuhn *et al.* 2010; Nordstrom *et al.* 2013). Inadequate nutrition around the breeding islands would thus result in pups receiving less milk and incurring higher mortalities. Key prey species may shift farther north out of the feeding range of Pribilof fur seals. However, it seems unlikely that the fur seals would abandon their current breeding islands in response and establish new colonies given that there are only 7 breeding Islands of fur seals in the entire North Pacific (NMFS 2007). In terms of meeting human needs, there is no other location close to the Pribilof Islands where fur seals could be obtained by the Aleuts living on the Pribilof Islands. However, subsistence takes are currently relatively low compared to the size of the fur seal population on the Pribilof Islands (NMFS 2005, 2014b), which means that the population would have to fall to much lower levels before a reduced take would likely be considered as a measure to conserve the fur seal population.

Bearded and Ringed seals - Although the adaptation of bearded seals pupping on land and ringed seals pupping is lairs is possible, it is likely in the transition, especially if ice loss is rapid, that pup mortality will be high. The shift to land for molting is also likely, with a lower impact on population numbers. The transition of both pupping and molting puts the seals at higher risk for disturbance and predation. The shift in habitat use will likely be sporadic and unpredictable for many years. There is potential development for site fidelity, but the transition time will likely be challenging for subsistence harvests.

Sea otters - The diving limitations and a need for rocky haulouts for pup care limit otters to the near-shore environment. Due to high energetic demands, otters must eat 25% of their body weight daily. Given these parameters, sea otters may not be very adaptable to climate changes that affect nearshore habitats and prey species. Sea otters will not be capable of range shifts across broad stretches of pelagic habitat; as such, this should not be an issue for hunters.

Management efforts to recover and increase the southwest sea otter population in the Aleutians may help mitigate potential impacts from climate change.

Whales – In general this group of species likely will adapt as evidenced by northern movement of minke, fin, and humpback whales into the Chukchi and Beaufort Seas. Harvests are already varying each year in quantity and timing and there is evidence that communities are likely to work more collaboratively to alter harvest practices so all communities' needs are met (NOAA 2013). To offset potential climate impacts managers can also continue implementing mitigation measures including protection of right whale critical habitat associated with resource development. Similarly investments to monitor the effects of increased shipping that include mitigation measures such as establishing shipping lanes to avoid key habitat may help minimize impacts to whales.

Chapter Recommendations

With an issue of such scope, complexity, and uncertainty, we offer the following recommendations for critical information needs to help understand risks faced by these marine mammal species. There are also potential mitigation measures that may be of use to managers and stakeholders in the ABSI region to help offset potential stressors from climate change.

Walruses – Key information needs include updated diet information, prey abundance and trends, as well as a greater understanding of the effects of ocean acidification on prey species. To improve understanding of walrus population levels, there is a need for region-wide stranding (mortality) surveys. Stranding surveys are primarily ad-hoc, opportunistic, and incomplete and are the only source of information on mortality factors other than hunting. There is also a need to understand and monitor the effects of increased vessel traffic to better inform potential mitigation measures.

To offset potential effects of climate change managers and stakeholders should maintain, and where needed increase, walrus coastal haulout protections as well as continuing implementation of mitigation measures associated with resource development. Large populations are likely better able to adapt to or withstand the detrimental effects of climate change. Self-regulation of the harvest by hunters will become important if the population declines. A reevaluation and potential reduction of the hunting struck and lost rate would also be important. Quotas on the harvest of adult females resulted in a population increase in the 1970s-1980s (Fay *et al.* 1997) and may also become important to maintain the population at desired levels.

Fish distributions may also shift to the north in the future and may result in an increased area of overlap with the southern distribution of walruses. Interactions among walruses and commercial fisheries have been very limited and unimportant in terms of walrus population size and demographics (USFWS 2013). Commercial fisheries are well regulated, but if fishing is expanded within the range of the Pacific walrus, additional monitoring will be required to detect any potential negative impacts.

Steller Sea Lions – Recommendations include the need to determine pregnancy and natality under current climate conditions. This will provide documented numbers for comparison as the impact of storm surges change in frequency and intensity. Facilitation of a collaborative approach to address climate change stressors on sea lions including partnerships with NOAA, ADF&G, the Alaska Sealife Center and universities on current work would also be beneficial.

Northern fur seal - Monitoring of northern fur seal numbers, diets, and terrestrial spaces used by them should continue on Bogoslof Island and the Pribilof Islands to ascertain causes of the Pribilof declines and to detect possible effects of climate-induced changes to the ecosystem and rookeries. Particular attention should be paid to the health and condition of pups, as well as to the foraging locations and behavior of lactating fur seals. This information can be obtained through collaborative research and monitoring by NOAA, the Alaska Sealife Center, Tribal Governments, and University researchers (NMFS 2007).

Ringed Seals - Recommendations for ringed seals include monitoring and documentation of ring seal shifts to land use. If this behavior becomes common and there is risk of potential disturbance, seasonal refuge areas might be established during pupping and molting. Close monitoring and potentially limiting fisheries that may impact prey close to haulout areas is recommended, as is monitoring the effects of increased vessel traffic and development of mitigation measures if needed. US adoption of the shipping Polar Code, self-regulation of the harvest by hunters, and reducing hunting struck and lost rate is encouraged.

Bearded seals – Recommendations for bearded seals would include the development of tools to measure impacts of climate change on animals (condition, pelage, pupping) with controlled captive studies. There is also a need for monitoring and documentation of bearded seal shifts to land use. Assuming sites were documented then consideration should be given to establishing seasonal refuge areas during pupping and molting, and limit fisheries that may impact prey close to haulout areas is recommended. Partnership with NOAA, ADF&G, the Alaska Sealife Center, the Ice Seal Committee and impacted communities on current work on ice seals would be beneficial.

Whales – To understand potential change effects, there is need for studies on habitat use for whale species. Examples of possible work include gathering TEK to monitor changes in species distribution as well as conducting tagging and tracking studies. These would be of particular importance to understand habitat needs of Right and Bowhead whales. This would include necropsy studies to document whether fall/winter feeding is occurring in ABSI LCC area; determining prey partitioning by species and general population monitoring.
As the northern latitudes ABSI region become more accessible due to the longer ice-free season it will be important to understand potential impacts of anthropogenic noise. Many of the species in this region lack basic thus making it difficult to understand the effects of changing noise in the marine environment (Southhall *et al.* 2007).

Sea Otters- Research needs include continued monitoring of sea otter distribution and abundance in the ABSI region to assess effects of climate change; continued stranding assessments, especially for the purpose of evaluating disease, biotoxins, and other threats; assessments of prey productivity, abundance, and trends at the species level; assessments of the effects of ocean acidification on prey species; assessments of the effect of increasing storminess on juvenile and subadult sea otters. Management efforts should include minimizing threats (including sea otter predation, infectious diseases, biotoxins, food limitation, disturbance, loss of habitat, contaminants, oil spills, bycatch in fisheries, subsistence harvest, and illegal take) and sources of take and insuring the availability of nearshore prey species.

Citations

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Chapter 6: Exploring Vulnerabilities of Seabirds Using Projected Changes in Climate in the Aleutian Islands and Bering Sea

William Koeppen, Katherine Kuletz, Aaron Poe, Heather Renner, Melanie Smith, Thomas Van Pelt, Nathan Walker, and Jeff Williams

Summary

- Changes in climate are expected to have both direct (e.g. storminess affecting energy expenditure and nesting success) and indirect (trophic level cascades) effects on seabirds.
- We took an exploratory look at projected changes for physical drivers and biomass of lower trophic level forage species in localized areas of important seabird habitat
- We used previously identified Important Bird Areas (IBAs) as focus areas to analyze vulnerability to climate change (via projections of biomass changes) for seabirds.
- We analyzed change in two ways, comparing historical/future time periods between two different models, as well as current and future time periods within one model.
- We examined the results of our analysis to identify IBAs with a mean value projected to change by one or more standard deviations between the two time periods. We flagged which places and variables were projected to change significantly, and whether the change was in a positive or negative direction.
- We then used that information to make interpretations about the places and species that are most vulnerable to climate change by 2040.
- Results indicate that species that rely on benthic resources (e.g. sea ducks) are most vulnerable to projected changes in forage biomass.

Introduction

Globally, the measurable impacts of climate change on oceans include decreased productivity, altered food web dynamics, shifted species distributions, and greater incidence of disease (Hoegh-Guldberg and Bruno 2010). These changes are often attributed to long-term increases in ocean temperatures resulting from climate change (e.g., Sydeman *et al.* 2012, Quillfeldt and Massello 2013). These changes in climate are also thought to have cascading effects on seabirds by indirect mechanisms that change water column characteristics (Ainley and Hyrenbach 2010) and food webs resulting in changes in prey availability (Barbraud *et al.* 2012, Dorresteijn *et al.* 2012, Thompson *et al.* 2012a).

Seabirds in the North Pacific mainly rely on two prey groups: forage fish and squids, and zooplankton (Sydeman *et al.* 2012). These prey species are thought to be strongly influenced by climate-driven changes in phytoplankton productivity (e.g. Behrenfeld *et al.* 2006), which in turn cause changes in the abundance and fecundity of zooplankton like copepods and euphausiids. Such potential changes in biomass at this level can translate into changes in the biomass or distribution of pelagic fish or squid, though mechanisms for these changes can be difficult to quantify. For example, Dorresteijn *et al.* (2012) suggested that warming climate is likely to have a negative impact on planktivores in the southeastern Bering Sea by decreasing food availability. Similar responses have been observed in other areas of the North Pacific (Kitaysky and Golubova 2000, Sydeman *et al.* 2006, Hipfner 2008, Bond *et al.* 2011), but some studies have shown contrasting effects of sea temperature on planktivores versus piscivores (e.g., Kitaysky and Golubova 2000). Responses will likely differ across foraging guilds and locations.

Variations in the responses of species result from differing abilities to adapt to shifts in prey distribution and general forage availability (e.g., Furness and Tasker 2000). Few studies have tested this hypothesis (e.g. Jaksik and Farina 2010) and some species of seabirds may be buffered sufficiently to overcome nutritional deficits and reproduce successfully (Grémillet *et al.* 2012). Further, localized effects on food webs may be confounded by other environmental drivers, such as strong upwelling regimes (Parrish *et al.* 2007), effects from commercial fishing activity (e.g., Chambers *et al.* 2014), or changes in sea ice (Provencher *et al.* 2012).

In the Aleutian and Bering Sea Islands (ABSI) region, the long term effects of changing sea ice extent and slight projected increases in storminess are additional considerations when trying to assess seabird species vulnerability to a changing climate. Given the complexities in understanding species response, we took an exploratory approach to understanding species vulnerability. As part of this effort we examined projections for physical drivers and biomass of forage species in localized areas of important seabird habitat. Through this approach, we strived to identify specific localities within the ABSI region where large environmental changes are most likely to occur, and consider the effects of those projected changes relative to our representative seabird species.

Evaluating exposure to climate change:

Although nearly 80 bird species have been encountered in the ABSI area, approximately 35 seabird species breed in the area, and another 20+ species regularly migrate there to feed during the summer. Our assessment didn't focus on any particular species but rather an exploration of key seabird habitat within the region. Smith *et al.* (2014a, b) completed an updated analysis of Important Bird Areas (IBAs) throughout the marine areas of Alaska. They used a spatial analysis of at-sea and aerial survey data to delineate polygons for important bird habitat associated with concentrations of birds in pelagic and coastal areas as well as areas surrounding seabird colonies. Within the ABSI region these polygons range in size from 40 km^2 (Attu Island Colony) up to 29,873 km^2 (St. Lawrence Island Polynya). Figure 1 shows an example of the distribution of Marine, Coastal, and Colony IBAs within the ABSI region. The IBAs are distributed across the ABSI region from the western Aleutians to the Pribilofs and to the eastern Bering Sea shelf, as well as north to the Bering Strait. To prioritize areas for this project, we used IBAs as focus areas to analyze vulnerability to climate change for seabirds. IBAs work well for this purpose because they represent places that have been identified supporting at least 1% of the world's population of the bird species for which they were established (Smith *et al.* 2014b).

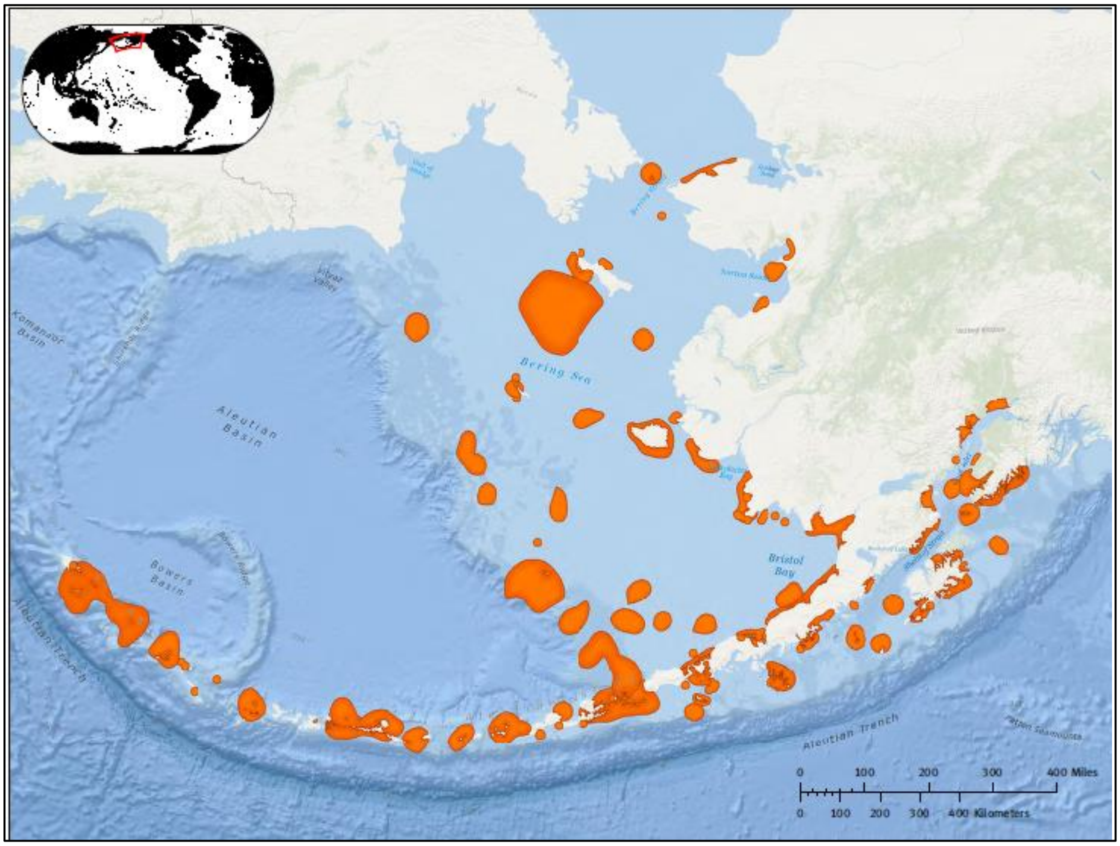

Figure 1. Important Bird Areas (IBAs) in the Aleutians and Bering Sea. Their full distribution is available online at: http://gis.audubon.org/PacificFlyway_IBAs/#

Methods

We began by evaluating projections of downscaled variables including physical (e.g. sea temperatures) and biological (e.g. benthic biomass) features. These projections were based on coupled ocean-climate models that pair a Regional Ocean Modeling System (ROMS) with climate model output extracted for the North Pacific from global climate models (GCMs). The delta method downscaled variables have a spatial resolution of 10×10 km (100 km^2) and many variables also include projections for multiple depth classes (e.g, density of euphausiids in different sections of the water column). Hermann *et al.* (2013) describe these projections more fully and compare projections from three CMIP3 GCMs (MIROC3.2 (medres), ECHO-G and CGCM3.1 (T47), all under the SRES A1B emissions scenario) to the Co-ordinated Ocean-Ice Reference Experiments (CORE) hindcast climate model (Large and Yeager 2008). Data are available as raster layers on the AOOS website. Their work results in projections of annual simulation of change in the Bering Sea and Aleutians from 1970 through 2040.

Based on anticipated increases in sea surface temperatures and a decrease in sea ice (extent, thickness, and seasonal duration), as well as changes in biomass of key lower trophic level species food web species, we identified seven variables of potential interest for seabirds (Table 2). Though seabirds may not directly prey on all of these classes we assumed their densities would be an indicator for the presence of other important forage species (e.g., forage fish). Four of these variables were assessed using three different depth classes: 0–5 m, 10–60 m, and 75–200 m. These categories represent forage availability for: surface feeders (e.g., kittiwakes [*Rissa* spp]); divers (e.g, murres [*Uria* spp]) and the deeper water column where mobile prey might occur and be available for birds during certain diel periods.

Table 2. Physical and biologically derived variables considered in this assessment, based on downscaled, coupled climate and ocean models by Hermann *et al.* (2013).

Physical Variables:
Sea Surface temperature (degrees C)
Sea Ice Cover (% ice fraction area)
Biologically-derived Variables:
Microzooplankton (mg C/m^3)*
Small copepods (mg C/m^3)*
Neocalanus copepods (mg C/m^3)*
Euphausiids (mg C/m^3)*
Benthic infauna (mg C/m^3)

*depth average for three categories: 0-5 m, 10-60 m, 75-200 m

We chose two different approaches to look at change between the reference condition and future condition for these variables. The first approach compared a historical time period to a future time period; the other compared a current time period to a future time period. The historical/future comparison gave us the best indicator of trend over a longer time period, and allowed us to compare a hindcast model based on observed data to a future state. We used the CORE model data from 1969–2005 to represent the historical time period, and the CCCma model from 2003–2040 to represent the future time period. The second approach compared a current time period (2003-2021) to a future time period (2021-2040), both from the CCCma model only. The advantage of the current/projected comparison was removing potential between-model bias. However comparing two ~ 20-year periods in a system known to have high variability between decades also has disadvantages.

We used the NetCDF Operator (NCO) Suite (e.g., Zender 2008; Zenter *et al.*, 2012) to statistically analyze and summarize the entire CORE and CCCma model time-series. Individual values for each cell in the resulting data structure were calculated by computing the mean and standard deviation for the time periods of interest from the weekly time slices output by the climate model. We also calculated the area-wide mean and standard deviation of the region, $\mu \pm \sigma$, as a reference value. The same approach was used for the historic/future (CORE to CCCma) and current/future (within CCCma) time comparisons.

Using iPython, we plotted summary maps showing the difference between reference condition and future condition means and standard deviation for each cell to show area-wide gradients of projected change for all variables at the surface. As an example, Figure 2a shows projected change in sea water temperature between 2003–2021 and 2021–2040 (or current/future as we have described it), based on projections of the CCCma model, where red shading represents an increase (throughout most of the study area) and blues a decrease. Concurrently, Figure 2b is an example of the change in standard deviation between time periods for SST, showing much higher variability (SD) occurring north of ~ 60°N in the Bering Sea. Change gradients for the seven variables from each of the model comparisons are included as Appendix A.

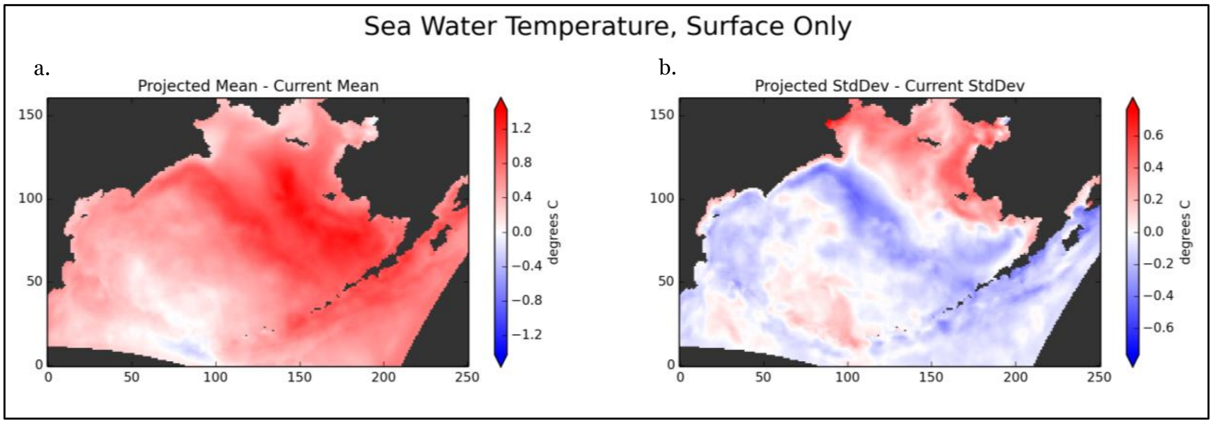

Figure 2. Projected change in sea surface temperature from 2003–2021 to 2021–2040 based on the CCCma coupled ocean-climate model where red indicates a projected increase and blue a projected decrease. (a) shows future mean minus current mean and (b) shows the average standard deviation from the mean.

Next, we created a standard deviates map for the project area (the full extent of the climate change projections). The standard deviate value is the cell value (a calculation of the mean across the time period) minus the mean of all cell values, divided by the standard deviation of all cell values. Converting each cell to a value representing the number of standard deviates from the area-wide mean allows us to then subtract the reference layer from the future layer, resulting in a layer representing the projected number of standard deviates of change at each cell location. This whole process can be calculated in one step, summarized in the following equation:

$$((\text{CellValue}_{\text{Future}} - \text{AreawideMean}_{\text{Reference}})/\text{AreawideSD}_{\text{Reference}}) - ((\text{CellValue}_{\text{Reference}} - \text{AreawideMean}_{\text{Reference}})/\text{AreawideSD}_{\text{Reference}})$$

Using this approach allowed us to simplify large amounts of disparately scaled data to a cell value that describes the reference condition (historical or current) and the future condition on an equal scale to facilitate comparison across variables.

The next step was to sample the maps to consider change just within the IBAs. Given the complex boundaries of the IBA polygons (Figure 3) we created bounding boxes to focus the analysis on the spatial extent of each IBA. These bounding boxes were used to sample cells from the raster surfaces (e.g., Figure 2) for the variables being considered by calculating a mean of the cell values included within each box. The result is a summary value representing both the temporal and spatial nature of each variable, calculated as a mean of the cell values within the IBA bounding box. Given that the cell size for the projected input data was 10×10 km we only considered results from IBAs with a total spatial extent of greater than 500 km^2 (five or more cells of data). This spatial requirement resulted in 78 of the total of 117 IBAs in the study region being considered in our analysis. These included a mix of colony, coastal, and marine IBAs.

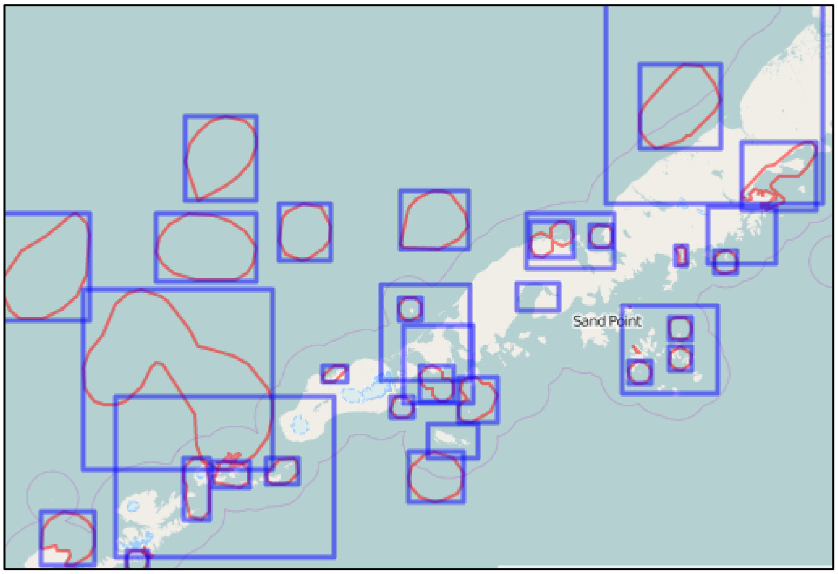

Figure 3. An example of bounding boxes around the tip of the Alaska Peninsula used to summarize the mean of 10×10 km raster cells to be representative of projected values within IBA polygons.

We interpreted the results of our analysis to identify IBAs projected to change by one or more standard deviates from the reference mean. We identified standard deviates of 1.0 or more (regardless of direction of the change) as being "significant" changes in that variable within that IBA. We also calculated relative ranks to identify those IBAs with the greatest amount of change for each variable (regardless of SD value). We then utilized that set of information to make interpretations about the places and species that are most vulnerable to climate change by 2040. We assumed IBAs with significant negative changes in forage biomass or sea ice and IBAs with significant changes in sea surface temperature might have negative implications for seabirds. Given that IBAs are established around concentrations of species (Smith *et al.* 2014b), we next looked to see if exposure to the projected changes may have any obvious negative implications at the species level. For example, if a projected loss in euphausiids occurred in IBAs that support murres, this might be a greater concern than changes in benthic biomass that is not directly used by that species.

Results

The most significant negative changes in forage resources appear to be for the density of benthic biomass within IBAs. For IBAs with a mean value projected to change by ≥1.0 standard deviation from the reference mean, 21 were identified in the historical/future comparison as having significant decreases between 1970 and 2040 (Table 3). Similarly projected decreases in benthic biomass were found for six IBAs identified in the current/future evaluation for 2003-2040 (Table 4). Decreases in benthic biomass are concentrated in the area of the middle Bering

Sea shelf, including Bristol and Kuskokwim bays and the Alaska Peninsula, but do extend up to the Bering Strait (Figure 4).

The group of bird species identified within these IBAs that may be most impacted are sea ducks, given their reliance on benthic invertebrates. Within the current/future comparison, Jacksmith Bay to Cape Pierce, Kuskokwim Bay, and Marmot Bay all were chosen in part because of their global significance for supporting sea ducks including Steller's Eiders (*Polysticta stelleri*), which are listed as Endangered under the U.S. Endangered Species Act. Within the historical/future comparison, these same three IBAs were also identified as undergoing significant decreases in benthic biomass. An additional eight IBAs with projected decreases in benthic biomass that support seaducks included: Cape Vancouver, Eastern Kodiak Island Marine, Northern Alaska Peninsula Coastal, Nunivak Island, Nushagak and Kvichak Bays, Port Moller, Sitkinak Strait, and Stebbins-St. Michael (Figure 5)

Figure 4. Twenty-one Important Bird Areas (IBAs) with a projected significant decline in benthic biomass from 1970-2040 based on a comparison of CORE and CCCma models

There were no significant declines in any of the depth categories for all four other forage classes (microzooplankton, small copepods, neocalanus, and euphausiids) within the current/future comparison between 2003 and 2040. Similarly, there were no significant changes in the two uppermost depth classes (0–5 and 10–60 m) for these same four forage classes within the historical/future comparison from 1970–2040. However there were projected decreases in these forage classes in the 75–200 m depth class at four IBAs (Appendix B). Wide Bay had projected decreases in all four forage classes within this depth category. Sitkinak Strait showed projected declines in microzooplankton, small copepods, and euphausiids. Cherni Island Complex Colonies and Cape Douglas to Amalik Bay showed a projected decline in *Neocalanus* at this depth. Given the depth class it's not clear that seabirds might directly experience loss of forage.

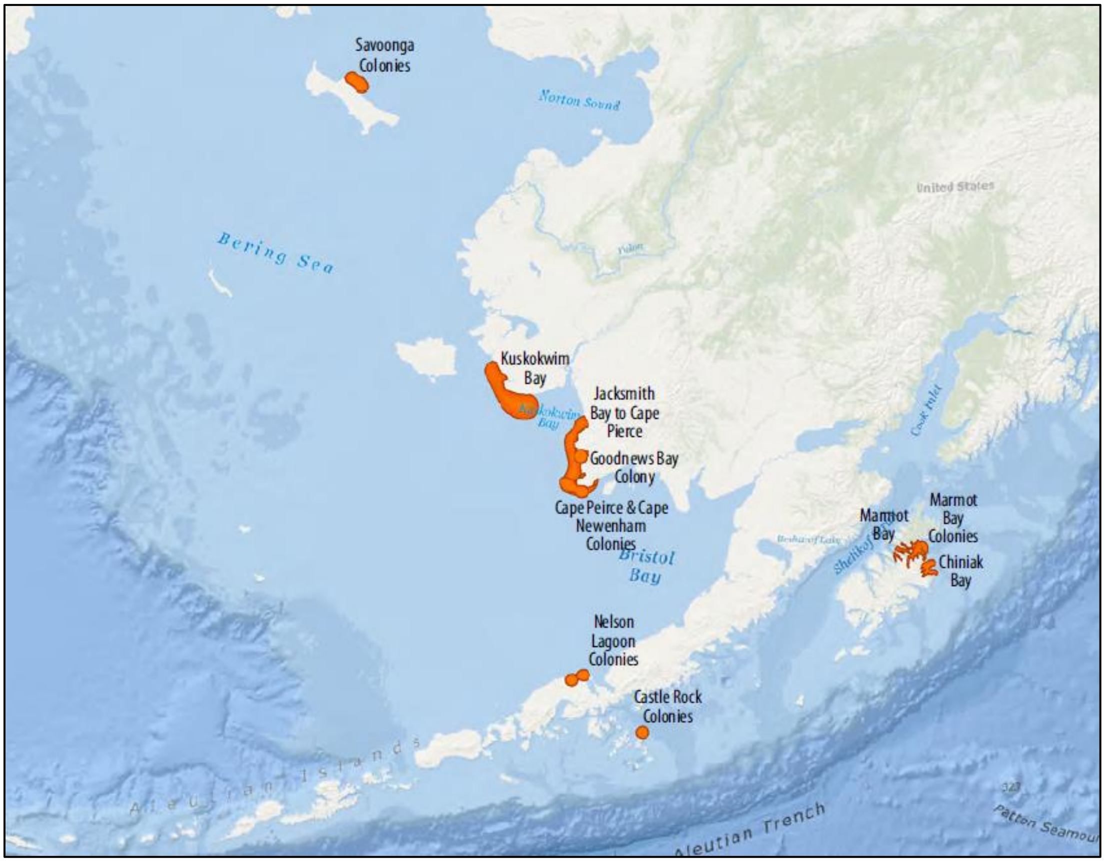

Figure 5. Nine Important Bird Areas (IBAs) supporting the Endangered Steller's Eider with a projected significant decline in benthic biomass from 1970-2040 based on a comparison of CORE and CCCma models.

Table 3. Important Bird Areas (IBAs) with a projected significant decline (SD > -1.0) in benthic biomass from 1970-2040 based on a comparison of CORE and CCCma models.

IBA Name	Area (km2)	Type	Species	Benthic SD
Akun Strait Colonies	557	Colony	Double-crested Cormorant, Red-faced Cormorant, Tufted Puffin	-1.25
Baby Islands & Akutan Pass Colonies	1,022	Colony	Cassin's Auklet, Double-crested Cormorant, Fork-talied Storm-Petrel, Leach'sStorm-Petrel, Red-faced Cormorant, Tufted Puffin	-1.05
Bering Sea Shelf Edge 173W58N	2,153	Marine	Fork-talied Storm-Petrel; Northern Fulmar	-1.00
Bering Strait	2,019	Marine	Crested Auklet; Least Auklet; Parakeet Auklet; Red Phalarope	-2.42
Cape Vancouver Marine	690	Coastal	King Eider; Steller's Eider	-2.31
Eastern Kodiak Island Marine	2,124	Marine	Aleutian Tern; Black Scoter; Glaucus-winged Gull; Harlequin Duck; HEGU; King Eider; Long-tailded Duck; Marbled Murrelet; Mew Gull; Pigeon Guillemot; Pomarine Jaeger; Red-necked Grebe; Sooty Shearwater; Steller's Eider; White-winged Scoter	-2.27
Hegemeister Island Colonies	712	Colony	Pelagic Cormorant	-1.11
Ilnik Marine	2,965	Marine	Black-legged Kitiwake; Glaucus-winged Gull; White-winged Scoter	-1.14
Jacksmith Bay to Cape Pierce	2,678	Coastal	Black Brant; Black-legged Kitiwake; Black Scoter; Emperor Goose; Greater Scaup; King Eider; Mew Gull; Steller's Eider; White-winged Scoter	-1.09
Kuskokwim Bay	3,077	Coastal	Black Scoter; Common Eider; Glaucous Gull; Long-tailded Duck; Red-throated Loon; Steller's Eider	-2.52
Marmot Bay	652	Marine	Black Scoter; Harlequin Duck; Long-tailded Duck; Marbled Murrelet; Mew Gull; Pigeon Guillemot; White-winged Scoter	-1.02
Nelson Lagoon Colonies	618	Colony	Aleutian Tern, Glaucus-winged Gull, Mew Gull	-1.10
Northern Alaska Peninsula Coastal	3,002	Coastal	Black Scoter; Dunlin; Emperor Goose; Glaucous Gull; Glaucus-winged Gull; King Eider; Long-tailded Duck; Mew Gull; Northern Pintail; rock sandpiper; Steller's Eider; White-winged Scoter	-1.07
Nunivak Island Coastal	4,326	Coastal	Aleutian Tern; Black Brant; Common Eider; Common Murre; rock sandpiper; Steller's Eider	-1.47
Nushagak & Kvichak Bays	4,245	Coastal	Black-bellied Plover; Black Scoter; Dunlin; Emperor Goose; Greater Scaup; Glaucus-winged Gull; King Eider; Long-tailded Duck; Mew Gull; Steller's Eider; Tundra Swan; White-winged Scoter	-1.81
Port Moller	1,485	Coastal	Black Scoter; Common Eider; Emperor Goose; Glaucous Gull; Glaucus-winged Gull; King Eider; Long-tailded Duck; Mew Gull; Steller's Eider	-1.04
Savoonga Colonies	700	Colony	Crested Auklet, Least Auklet, Pigeon Guillemot	-1.17
Sitkinak Strait	994	Coastal	Black Scoter; Emperor Goose; Glaucus-winged Gull; Marbled Murrelet; Steller's Eider	-1.74
Southwest Cape Colonies	635	Colony	Black-legged Kitiwake, Common Murre, Crested Auklet, Least Auklet, Pelagic Cormorant, Pigeon Guillemot, Thick-billed Murre	-1.62
Stebbins-St. Michael	950	Coastal	Black Scoter; Dunlin; Red-necked Phalarope; Semipalmated Sandpiper; Tundra Swan	-1.06
Western St. Lawrence Island Marine	2,645	Marine	Crested Auklet; Least Auklet; Parakeet Auklet; Spectaled Eider	-1.63

Table 4. Important Bird Areas (IBAs) where there is an expected significant decline (SD > -1.0) in the amount of benthic biomass between 2003 and 2040 according to projections by the CCCma coupled ocean-climate model.

IBA Name	Type	Area (km2)	Species	Benthic SD
Cape Peirce & Cape Newenham Colonies	Colony	799	Black-legged Kittiwake, Common Murre, Double-crested Cormorants, Glaucus-winged Gull, Pelagic Cormorant, Tufted Puffin	-1.03
Jacksmith Bay to Cape Pierce	Coastal	2,678	Black Brant; Black-legged Kittiwake; Black Scoter; Emporer Goose; Greater Scaup; King Eider; Mew Gull; Steller's Eider; white-winged scoter	-1.13
Kuskokwim Bay	Coastal	3,077	Black Scoter; common eider; Glaucous Gull; Long-tailed Duck; Red-throated Loon; Steller's Eider	-1.02
Marmot Bay	Marine	652	Black Scoter; Harlequin Duck; Long-tailed Duck; Marbled Murrelet; Mew Gull; Pigeon Guillemot; white-winged scoter	-1.51
Nelson Lagoon Colonies	Colony	618	Aleutian Tern, Glaucus-winged Gull, Mew Gull	-1.13
Savoonga Colonies	Colony	700	Crested Auklet, Least Auklet, Pigeon Guillemot	-1.33

Discussion

Assuming our significance test of ± 1.0 standard deviation change between time periods is reasonable, the majority of projected forage availability for species in the water column will not change dramatically. However there are 21 IBAs where the benthic biomass is projected to significantly decrease. These findings echo those of Hermann *et al.* (2013) when they compared the three different coupled climate models (including the CCCma) to the CORE model; they projected a northward shift in benthic biomass resulting in overall decline on the eastern Bering Sea shelf. Our evaluation showed that there are projected decreases in benthic biomass in 11 IBAs that are important to seaducks (Figure 4) based on the historical/projected (1970-2040) comparison. These IBAs are mostly in the northern part of the ABSI region, where we also found a significant projected increase for the Bering Sea Shelf IBA (169W60N) for the current/future model comparison (2003-2040).

Given that decrease in benthic biomass within IBAs on the eastern Bering Sea shelf were detected in both of our model evaluations, and are corroborated by the Hermann *et al.* (2013) results, our projections are reasonable. These declines in benthic biomass are expected to be the results of decreased amounts of nutrients making it to the ocean floor as a result of rapid sea ice retreat in the spring (e.g.,Grebmeier *et al.* 2006, Grebmeier *et al.* 2010). A number of recent studies link these changes in with sea ice extent with changes in benthic foodwebs through the *oscillating control hypothesis* (Hunt *et al.* 2011). Similarly, our results suggest that among marine birds, the benthic-feeding birds, ie, sea ducks could be particularly vulnerable to climate change due to a decrease in forage availability. These findings are also consistent with long-term changes in the distribution of preferred benthic prey species documented in the northern Bering Sea (Grebmeier 2012, Grebmeier *et al.* 2006), which have been suggested to affect eiders (Cooper *et al.* 2013, Lovvorn *et al.* 2009, 2015). The Steller's Eider, a federally listed Endangered Species, may be particularly at risk given the projections about IBAs on the eastern Bering Sea shelf that are globally significant for this species. Of the 15 IBAs supporting this species in the ABSI region, nine are projected to have significant declines in benthic biomass between 1970 and 2040. Steller's Eider has been identified as a *priority species* by the U.S. Fish and Wildlife Service based on population declines though much of the their focus relates to changes on the breeding grounds (USFWS 2014 Conservation Framework *unpublished*) and doesn't expressly address potential changes in the marine environment. Given that the historical/future comparison looks at a time continuum of 1970–2040 this decline in forage availability may have already contributed to their current conservation status. Decreases in the availability of benthic biomass may also be a stressor on Spectacled Eiders (*Somateria fischeri*) in the ABSI region which is another *priority species* exhibiting population declines (USFWS 2014 Conservation Framework *unpublished*).

We did not detect significant changes for any of the other four forage classes considered (microzooplankton, copepods, neocalanus, and euphausiids) expect in the case of four IBAs, and then only in a depth class that is not directly available to seabirds (70-200 m). However, Hermann *et al.* (2013) projected a northward shift and general increase in these four types of pelagic biomass. We observed similar patterns in both of our modeling efforts (Appendix A) but these changes did not appear to be significant at the level of individual IBAs based on our threshold of evaluation (SD >1.0). Assuming our analysis of these projections is valid there may be less concern about forage availability for species feeding on plankton and euphausiids directly. However, it's difficult to say how apparent increases in biomass for these four classes of forage species might relate to forage fishes that prey on them and in turn the birds that feed on those fish.

Additionally, there was overall less change within the CCCma model projection across all of the IBAs. This is perhaps not surprising given that the window it evaluated was only ~37 years, whereas the temporal span was almost twice as long in the CORE to CCCma comparison. We observed some anomalies within the historical/future model evaluation. For example, within Cook Inlet (outside of our focal region yet included in the area where these projections were made) there were also significant increases in the four pelagic forage classes, but only in the deepest water depth category. Our evaluation also offered some counter intuitive projections in Cook Inlet and the Gulf of Anadyr, such as decreased water temperature and increased sea ice. These same trends were not observed in these areas in the CCCma-only comparison and thus might be a result of some artifact in the CORE model. Evaluations of two additional projections from Hermann *et al.* (2013) for these same suites of variables would prove useful in further exploring differences between models that could be important to seabirds.

Our significance threshold of 1.0/-1.0 was chosen as an arbitrary threshold at which we might say that change is expected. This threshold was based on similar change detection work in terrestrial systems, but may have resulted in only detecting very acute change. The projections by Hermann *et al.* (2013) could be explored in alternative ways (e.g., comparing projected distribution functions), which may be better at evaluating extremes with the projections. Our reliance on means may have impacted our ability to detect significant sea ice declines that others have projected for the Arctic in general (Wang and Overland 2012). Not a single IBA was projected to have a significant shift, although four IBAs within the vicinity of St Lawrence Island with SD values > -0.8 were close to this threshold and indeed are areas where sea ice extent is changing rapidly. Similarly, though marine water temperature increases have been observed within the Bering Sea since the 1990s (Overland and Stabeno 2004), this trend was not significant for any IBA.

Our analysis approach may have also had the unintended effect of muting the overall change within IBAs. We standardized the projected changes in all variables within these IBAs by normalizing them using mean and SD values from each variable from the entire extent of the downscaled projections. The physiography of the region is variable, ranging from deep basin around the Aleutians to the shallow Bering Sea shelf. Further, parts of the region are much more affected by sea ice dynamics than others. It may prove preferable to bin IBAs separately into a few different ocean regions, then relate change in IBAs to the mean and SD of those regions rather than the full study area.

We are confident that an analysis subdivided by regions that compared changes within IBAs with similar physiographic and oceanographic characteristics would not change our projected decline in benthic biomass for 21 IBAs. The directionality of those changes is very likely to stay the same when taking this more nuanced approach to analysis and the magnitude of those changes are likely to increase. Reanalyzing these projections using subdivide regions may also allow us to detect some decreases in sea ice, increases in water temperature, and perhaps better elucidate changes in the four other forage classes.

Compounding Stressors

In addition to direct changes in climate there are a number of climate-related changes that are also taking place which have implications for seabirds. For example, decreases in seasonal sea ice allows for additional vessel traffic into northern parts of the ABSI region (Smith and Stephenson 2013). Among the circumpolar routes, the Bering Strait area in particular has the highest overlap and associated risk between seabirds and human activities (Humphries and Huettmann 2014). The Bering Strait is a 'hotspot' of seabird density (Wong *et al.* 2014, Kuletz *et al.* 2015), due to its proximity to large breeding colonies (Stephenson and Irons 2003), apparent prey availability (Hunt 1997, Piatt and Springer 2003), and its use as a migration corridor (Kuletz *et al.* 2015, Lovvorn *et al.* 2015). Oil spills, or introductions of rats from vessel accidents as a result of increased traffic in this northern region, could have profound impacts on seabirds (AMSA 2009, Humphries and Huettmann 2014).

The effect of commercial fishing on the availability of forage biomass is a key consideration of compounding and confounding effects of climate change on seabirds. Fishing may also alter the amount and flow of energy in an ecosystem through the return of discards and fish processing offal back into the sea and through mortality from seabird bycatch (Livingston *et al.* 2011). Removals concentrated in space and time may impair the foraging success of animals tied to land such as nesting seabirds. Alternatively, removals of some predatory fish might also result in increased availability of prey species for seabirds. Chambers *et al.* (2014) reported that few studies explicitly considered non-climatic drivers of change, and these possibilities, such as interspecific competition or fishing pressures, should be considered (e.g., Brown *et al.* 2011, Woehler *et al.* 2014). Even given that the fisheries in Bering and Aleutians are typically regarded as well managed and sustainable (e.g., Worm *et al.* 2009), attempting to evaluate changes in climate would ideally also give careful consideration to fishery harvest dynamics.

Our exploratory evaluation that identifies a decline in benthic biomass, especially within the region of the eastern Bering Sea shelf, may also be exacerbated by ocean acidification (OA). Recent work by Takahashi *et al.* (2014) has identified the Bering Sea as having some of the most acidic marine waters on earth. Effects on marine invertebrates represent some of the earliest inquiry into OA and there appears to be substantial energetic cost involved with increased acidity on developmental processes for shellfish and zooplankton. This may come in part as a result of decreased calcification or shell dissolution in order to maintain internal chemistry (Gazeau *et al.*, 2007, Michaelidis *et al.*, 2005), or increased muscle wastage in order to maintain skeletal integrity (Wood *et al.*, 2008).

Increased acidity is likely to be especially acute in areas of the ABSI region where there is substantial freshwater intrusion (e.g., near shoreline and ice edges) which results in water capable of becoming more highly acidic. The effects of OA in IBAs where benthic invertebrates are already declining because of climate change may be especially problematic for sea ducks that depend on this forage resource. It's worth noting that some of the IBAs identified in our analysis are in the proximity of Kuskokwim Bay, which has a large influx of fresh water from terrestrial sources, and other IBAs are near sea ice-affected areas around St. Lawerence Island.

Adaptation

It's difficult to evaluate the adaptive capacity of seabird species to broad systematic changes in forage availability (e.g., Barbraud *et al.* 2011) or changes in physical variables like the distribution of sea ice (Provencher *et al.* 2012). Furness and Tasker (2000) developed a model to evaluate the adaptive capacity of seabird species to changes in forage availability. Something similar could help managers in the ABSI region better identify which species might be most susceptible to changes in forage availability.

Specific actions that managers could take to address some vulnerabilities to climate change are similarly difficult to identify. In other parts of the world marine protected areas have been established in hopes of protecting key feeding sites for seabird species from disturbance by human activities (e.g. Gremillet and Boulinier 2009). Certainly changes to commercial fishing activity could have benefits relative to increased forage availability. Cury *et al.* (2011) suggested that fisheries managers obligate one-third of maximum fisheries biomass (including krill) to maintain seabird populations, based on examination of the relationship between seabird productivity and maximum estimated prey biomass across 7 ecosystems and several decades. However, such direct action by managers would have to be rigorously justified and show a direct mechanism related to population decline. This is likely very difficult given the complexities in detecting trends in seabirds and isolating the effects of fishing within those trends.

Adaptation of seabird management is probably most restricted by a limited understanding of seabird population dynamics in the region and how they might relate to climate change. Research and analysis efforts to better connect availability of forage and seabird population trends in the ABSI area might be a key first step. Such information could improve current monitoring to focus on areas or species most likely to be impacted by changes in forage availability and could trigger compensatory management actions to minimize disturbance from others stressors on those species or areas.

Additional understanding of seabird population dynamics relative to productivity in the ABSI region might come from partnerships with NOAA Fisheries, aimed at identifying changes in forage availability that could be of interest to both seabird and fishery managers. Given that some seabirds and fish stocks feed on the same forage base, joint efforts among fisheries and seabird managers would improve our ability to detect and understand important changes in climate and adapt management strategies. Such efforts between fishery and seabird managers have been identified as necessary to better understand climate change as well as build capacity for adaptive management (Quillfeldt and Masello 2013)

Research Recommendations

Our initial modelling evaluation identified projected declines in benthic biomass but did not detect clear potential threats to other seabird species in the region. Some revisions to our modelling process like evaluating changes in IBAs relative to overall changes in subregions may prove useful. Examining availability of these four benthic forage classes seasonally, rather than as changes in total annual biomass, may also be useful.

There are effects relative to climate that won't be well addressed by further exploration for forage biomass projections alone. Given the complexities as to how changes in the lower trophic levels translate to total availability of forage (e.g., forage fishes and squid) for seabirds, more nuanced analyses may be necessary. These analyses could be improved by looking at climate change effects on guilds of seabird species. For example biologists with AMNWR have structured their long-term monitoring program based on foraging guilds such that they monitor trends in species or groups of species that are indicative of different foraging strategies (e.g,. diving piscivore, diving planktivore, surface piscivore, etc.) Further, given that there are several seabird species of conservation concern in the region, taking a broader look at potential effects of climate on those species would be instructive as well.

Based on work that has been done in other areas there are several research items that could help managers better understand risks to seabird species from climate change in the ABSI region. These recommendations are not prioritized and are organized into three thematic areas of inquiry:

Warming Oceans and Trophic Effects

- Evaluate Sea Surface Temperatures (SSTs) via hindcast projections compared to maritime seabird colony data and/or at-sea data to identify potential correlations—i.e., looking for correlations with SST Anomalies or SSTAs in the region's climate record (e.g., Quillfeldt and Masello 2013)

- Integrate projections from coupled ocean/climate models (e.g., the PMEL models used by Hermann *et al.* 2013) especially relative to: Nutrient-Phytoplankton-Zooplankton variables and individual-based population dynamics models (e.g., Leslie matrices) for various bird species to explore climate effects. An expansion of this project could incorporate an evaluation of the cumulative effects of ocean acidification and/or hypoxia.
- Develop a quantitative index of the sensitivity of different seabird species to reduced forage abundance, modelled after Furness and Tasker (2000). These could include: seabird body mass, cost of foraging, potential foraging range, ability to dive, amount of 'spare' time in the daily budget, and ability to switch diet.
- Develop population dynamics models to integrate changes in habitat and food resources (per predictive demographic framework; see above) to articulate (quantitatively) mechanisms of change. Subsequently, compare and verify using empirical data (Jenouvrier *et al.* 2009, Wolf *et al.* 2010).
- Expand use of physiological tools which directly relate nutritional stress to population processes (Kitaysky *et al.* 2007, 2010) at large geographical scales at reasonable expense (Satterthwaite *et al.* 2012, Dorrensteijn *et al.* 2012); e.g., measurements of the stress hormone corticosterone (Barbraud *et al.* 2012).
- Continue to collect information about seabird demography and begin work on genetics and connectivity (dispersal statistics) of seabird populations. As shown by Sandvik *et al.* (2012), fecundity and survival need to be measured simultaneously with concurrent measurements of the physical environment.

Winds and Storminess

- Expand COASST monitoring near selected sites and communities to establish baseline information on mortality and capture unusual seabird mortality events following storms.
- Explore correlations between seabird breeding success and weather events using Alaska Maritime Refuge's monitoring data compared to hindcast projections of storminess and/or weather observations derived from annual monitoring sites.
- Identify seabird species and sites most at risk to impacts on breeding habitat due to coastal erosion and flooding.

Sea Ice Changes

- Analyze fall distribution and abundance of seabirds with respect to physical and biological characteristics of fall oceanographic conditions using existing data.
- Census polynyas of northern Bering Sea in spring using ships of opportunity and drones to identify habitat characteristics of these sites and distribution and abundance.

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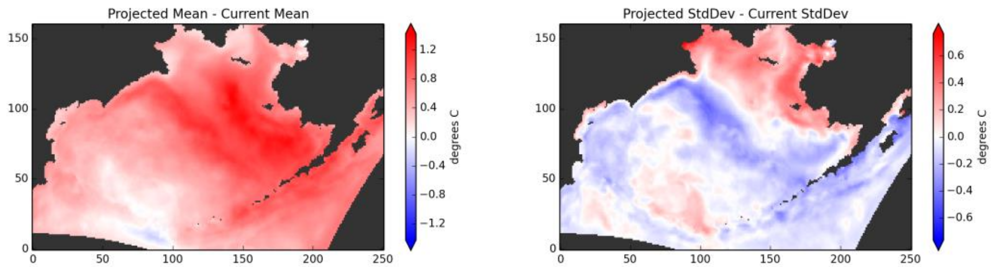
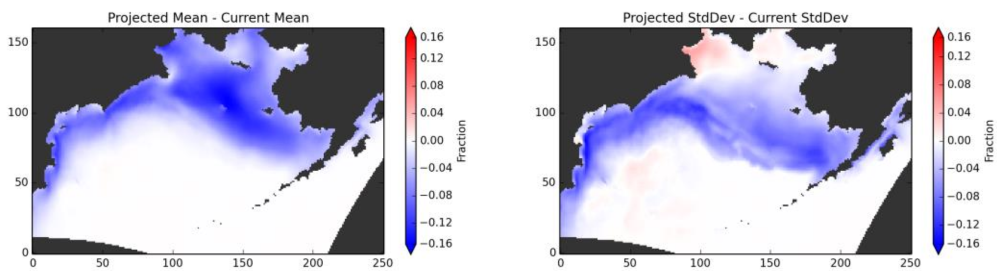
Appendix A. Projected changes in seven physical and biophysical variables in the ABSI Region

Projected changes in mean and standard deviation for the current/future comparison 2003-2040 (CCCma only).

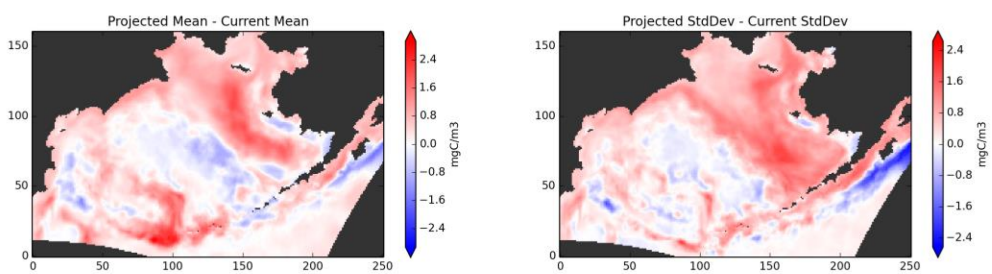
Sea Water Temperature, Surface Only



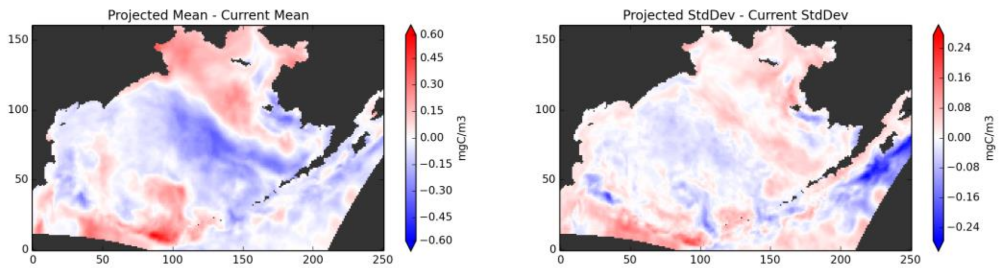
Sea Ice Area Fraction



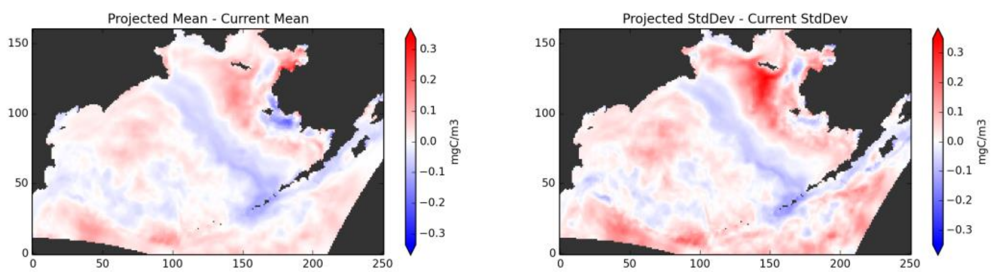
Large Microzooplankton Concentration, Surface Only



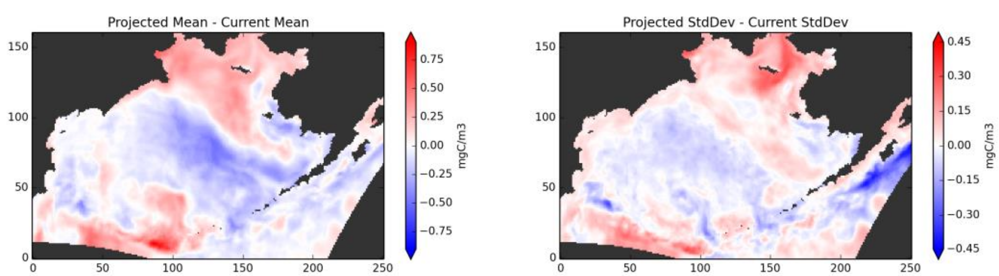
Small Coastal Copepod Concentration, Surface Only



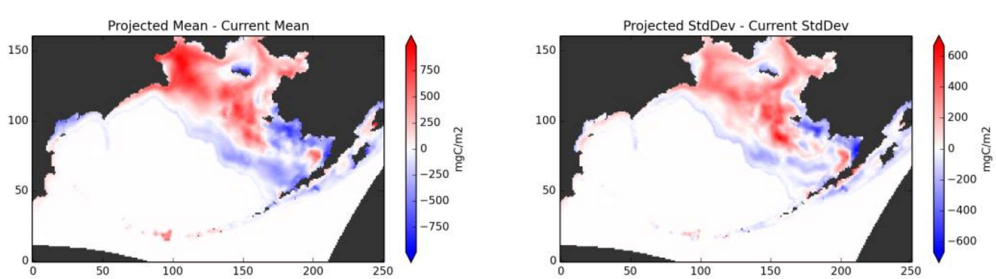
Neocalanus Concentration, Surface Only



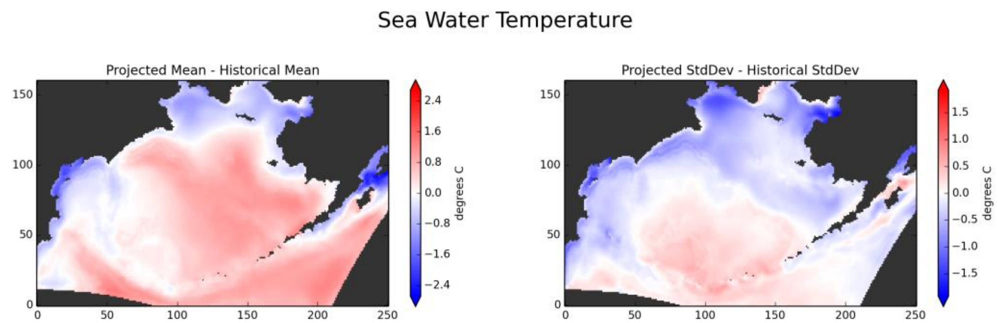
Euphausiids Concentration, Surface Only

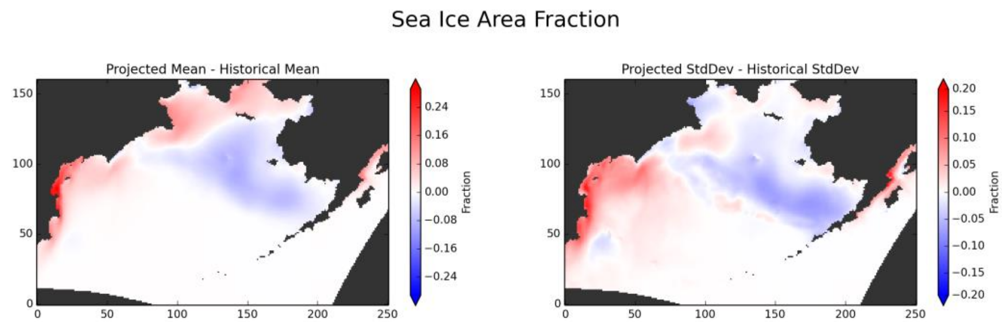


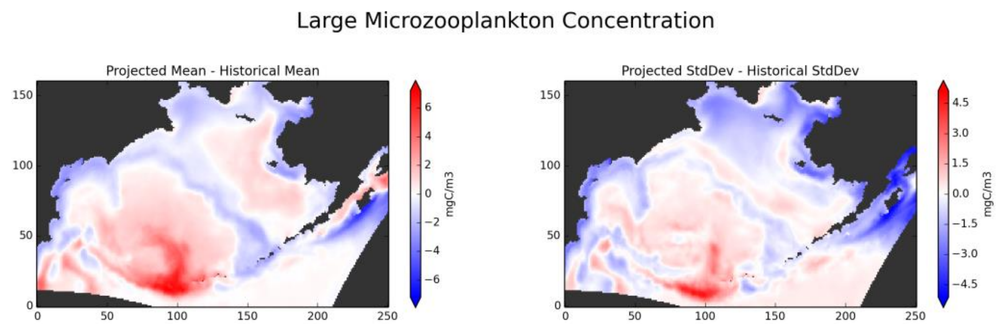
Benthos Concentration

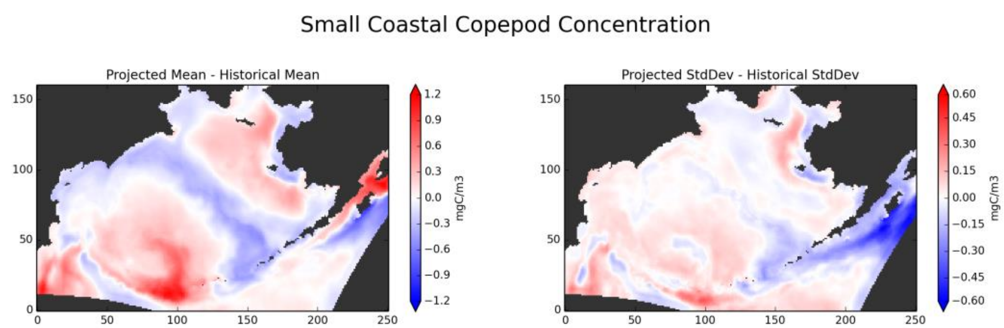


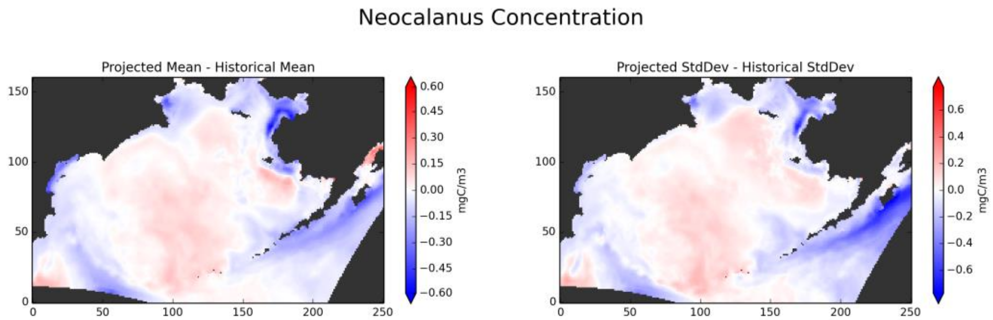
Projected changes in mean and standard deviation from the historical/future comparison 1970-2040 (CORE to CCCma)

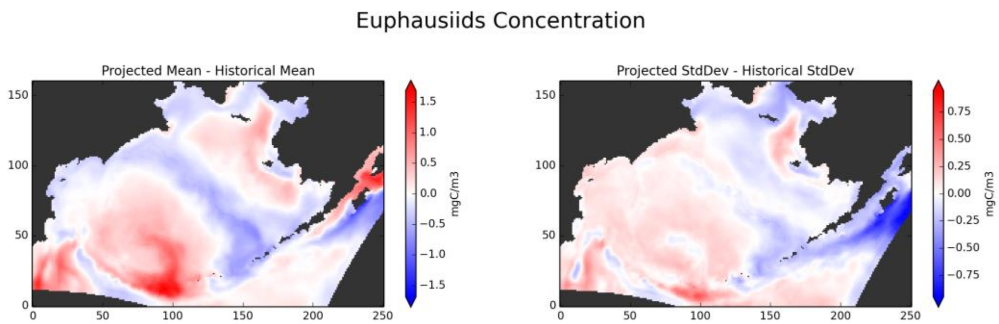


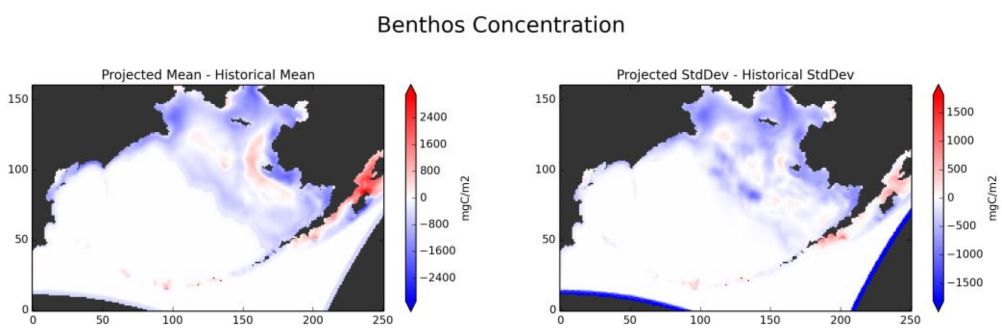







Neocalanus Concentration
Projected Mean - Historical Mean
mgC/m3
Projected StdDev - Historical StdDev
mgC/m3


Euphausiids Concentration
Projected Mean - Historical Mean
mgC/m3
Projected StdDev - Historical StdDev
mgC/m3


Benthos Concentration
Projected Mean - Historical Mean
mgC/m2
Projected StdDev - Historical StdDev
mgC/m2

Chapter 7: Overall Results, Discussion, and Implications: Structured Decision Making

Tuula E. Hollmén, Aaron Poe, Thomas Van Pelt, Ellen Tyler, Jeremy Littell

Summary

In the preceding chapters, the Aleutian-Bering Climate Vulnerability Assessment evaluated vulnerabilities of key species and ecosystem services in the Aleutian Islands and Bering Sea region relative to projected changes in climate. Extending existing marine research and leveraging from completed downscaled climate projections for the Bering Sea and Aleutian Islands region, a team of 30 researchers with expertise in components of the ecosystem convened to assess climate projections and develop research recommendations in the context of their expertise. These teams represented five components of the local ecosystem: terrestrial vegetation, fish/shellfish, seabirds, marine mammals, and humans. Each team identified initial vulnerabilities for their focal species or services, and made recommendations for further research and information needs that would help managers and communities understand the implications of the changing climate in this region.

To integrate and prioritize recommendations from the ecosystem component expert teams, we conducted a Structured Decision Making workshop and applied decision analysis tools to organize and rank recommendations within and among the components. Four of the five expert teams (fish/shellfish, seabirds, marine mammals, and humans) participated in the structured decision analysis workshop and are represented in the outcome recommendations. The first step of the process entailed a preparatory phase with the core planning team to frame the decision and define objectives. Input was gathered from a team of ecosystem component experts during a 2-day workshop, followed by ranking of input to synthesize recommendations within and among the components. The results of our process will be used to develop the climate research priorities for funding partners and will be shared with other entities funding and conducting research in the Aleutians and Bering Sea.

Introduction

The Aleutian and Bering Sea Islands Landscape Conservation Cooperative (ABSI LCC) and their two partner organizations the Alaska Ocean Observing System (AOOS), and the Alaska Climate Science Center (ACSC), periodically make decisions about what research projects to fund within the Bering Sea Large Marine Ecosystem. The Aleutian-Bering Climate Vulnerability Assessment (ABCVA) was initiated to assist the partner organizations by developing a prioritized list of research recommendations made by the expert teams and community contributions to this assessment. The ABCVA evaluated vulnerabilities of key species and ecosystem services in the Aleutian Islands and Bering Sea region relative to projected changes in climate. Extending existing marine research and leveraging from completed downscaled climate projections for the Bering Sea and Aleutian Islands region, a team of 30 researchers with expertise in components of the ecosystem convened to assess climate projections and develop research recommendations in the context of their expertise. These teams represented five components of the local ecosystem: vegetation, fish/shellfish, seabirds, marine mammals, and humans. Teams identified initial vulnerabilities for their focal species or services, and made recommendations for further research and information needs that would help managers and communities understand the implications of the changing climate in this region. The assessment work for the terrestrial vegetation team, though valuable, did not lend itself well to this process. Given the significant lack of information about climate change effects on vegetative communities, the authors of that chapter were not able to make specific research recommendations.

Structured Decision Making (SDM) analysis is based on decision theory, offering a framework and methods to organize and analyze decision problems. A structured process involved a stepwise articulation and analysis of components supporting the decision making process. The steps commonly employed in a structured decision analyses involve problem definition, articulation of objectives, development of alternative actions, predictions of consequences, and a step of optimization to choose among alternatives. The roots of the process lie in economic sciences and methods have been recently and increasing applied in natural resource management science. Most ecological applications to date involve decision-making to choose among alternative resource management actions, however, the concept of structured decision analysis is applicable to a suite of decision problems—including prioritizing research items against stated objectives. The decision analysis methods offer a diverse set of tools to organize, compare, and rank alternatives, allowing the incorporation of both empirical data and expert opinion with the framework. The structured decision analysis process offers a framework to address complex decisions, uncertainty, and stakeholder values (Gregory and Keeney 2002, Conroy and Peterson 2013).

The three partner organizations (ABSI LCC, AOOS, and ACSC) will incorporate recommendations on research priorities identified by the ABCVA ecosystem component expert teams. These recommendations will guide funding decisions by the partnering funding agencies. We applied SDM techniques to organize and integrate research priorities identified within the ecosystem components described by four of the assessment chapters of the ABCVA. Our main objectives were to first rank priorities and threats within each, and then develop a ranking framework for integration of research recommendations among the ecosystem components addressed by each of the four chapters.

Methods and Results

Preparation for workshop

We applied structured decision support tools to help the partner organizations (ABSI LCC, AOOS, and ACSC) develop integrated research priorities for the Aleutian Islands and Bering Sea region. The overall goal was to build a framework for integrating recommendations made by the ecosystem component teams, and to rank research priorities within and among the ecosystem components. Our process included three steps: 1) Framing the decision and development of objectives for ranking process; 2) Elicitation of expert input on ranking of recommendations in an SDM workshop; and 3) Synthesis of expert input into an integrated recommendation. The process involved a core planning team with representatives from each of the three partner organizations and an SDM coordinator as well as a group of subject matter experts representing the ecosystem components of the ABCVA (fish/shellfish, seabirds, marine mammals, and humans). This group worked together during the course of an SDM workshop held in Anchorage in December of 2014.

Prior to the SDM workshop, the core planning team held meetings to define the decisions to be addressed using SDM process, and to develop objectives for the integration and ranking process. The core team prepared for the planning meetings by answering a list of questions to help define the decision structure:

- What specific decision has to be made?
- What is/are the triggers for the decision?
- What is the action to follow?
- Who are the decision-makers and stakeholders?
- What are the spatial and temporal scopes of the decision?
- Will the decision be iterated over time?
- Are there specific legal/financial constraints? Regulatory mandates?

The core team drafted a decision statement and developed a list of objectives for the SDM process.

Decision problem. Each of the three partner organizations periodically make decisions about what research projects to fund within the Bering Sea Large Marine Ecosystem. The ABCVA is intended to assist the partner organizations by developing a prioritized list of research recommendations made by the expert teams and community contributions to this assessment. Decisions about research priorities are made by the staff and boards of the three partner organizations (ABSI LCC, AOOS, and ACSC). Stakeholders are the managers, researchers and community members living and working in this area.

Decision structure. The partner organizations are working on strategic plans that will incorporate recommendations on research priorities identified by the expert teams and community stakeholders. The recommendations and strategic plans will guide funding decisions by the funding/partner agencies. Three types of funding mechanisms are expected: 1) Core funding (e.g. a 5-year proposal or programmatic funding from ABSI, AOOS, or ACSC), 2) Full proposal (actively seek to fund through grant writing RFP), and 3) Low cost/highly leveraged opportunistic funding (programmatic investments as they arise).

The objectives guiding our SDM process were organized into a hierarchy of fundamental, means, strategic, and process objectives.

Fundamental objectives:

- Minimize vulnerability (maximize viability) of key resources/services
    - Address key species of concern (considerations: ecological function/role, conservation status/mandates, economic viability, subsistence use)
    - Address key climate mediated threats to those species (or their habitats)
    - Reduce key uncertainties about effects
- Minimize cost of research
- Maximize leverage and partnerships to support the research

Means objectives:

- Feasibility to address research question and reduce uncertainty
- Ability to manage

Strategic objectives:

- Maximize cross-component benefits among the four assessments (fish/shellfish, seabirds, marine mammals, humans)
- Maximize Bang-for-Buck (i.e., greatest potential impact from smallest investment)
- Maximize links and relevance to management
- Maximize awareness/understanding of climate effects (stakeholders, public)
- Maximize stakeholder satisfaction
    - Maximize public trust
    - Maximize links to management objectives
    - Maximize local community satisfaction
        - Maximize local community involvement
        - Maximize economic/subsistence benefits to local communities

Process objectives:

- Maximize inter-agency collaboration and overlap among agency priorities

It was decided that the expert workshop would focus on ranking criteria based on two of the fundamental objectives, minimizing vulnerability of key resources and minimizing cost. The other objectives would be addressed later by the core planning team as deemed necessary by the partner organizations to further support overall development of strategic research plans for the Aleutian and Bering Sea region.

Workshop

Expert input was elicited in a 2-day workshop with representatives from four of the five ecosystem component expert teams. The core planning team invited representatives from each of the ecosystem components. The goal was to engage expertise from each of the components, and balance the number of representatives among the components. Workshop Participants are listed in Appendix A.

The workshop agenda involved an introduction to SDM process, break-out sessions to develop ecosystem component rankings, and a shared session to integrate priorities (Appendix B). Ranking sessions were structured into three modules:

Module 1: Develop priority lists and ranking criteria by species and threats within each of the four ecosystem component teams

Module 2: Develop ranking criteria for integrated priorities

Module 3: Review research questions for cross-component relevance and assign scores to rank research questions for integrated priorities

We used a modified Delphi method (e.g., Dalkey and Helmer 1963) to elicit input from expert teams. Experts developed consensus rankings within their group using a constructed scale of 1-5 (low – high). Module 1 was conducted in breakout sessions by each of the ecosystem component teams. Modules 2-3 were conducted with the entire team working together.

In the breakout sessions, the component teams first constructed a table evaluating their species of concern using a suite of evaluation criteria. These criteria included ecological role, conservation/management concern, subsistence use, and commercial use. The teams scored each of the species for each criterion using the constructed scale 1-5. The seabird group organized their species by forage guild, and selected a representative species for each. The fish/shellfish and marine mammal team divided the Aleutian Bering Sea region into four sub-regions and provided rank scores for each species by the sub-region. Cumulative scores for each ranking criteria were used to develop a ranking order for species within the ecosystem components. This exercise provided a ranking of species based on the evaluation criteria, which could be used as a measure of vulnerability or level of concern.

In the next exercise, the component teams evaluated the list of threats developed by the ABCVA (Warming of ocean temperature, changes in cold pool extent/seasonality, ocean acidification, changes in sea ice extent and seasonality, shifting wind patterns/storminess, changes in freshwater discharge) using a suite of ranking criteria (scope of threat, immediacy, and number of species affected within their component). For each threat, both direct and indirect effects were considered, and a constructed scale of 1-5 was used for scores. Cumulative scores for each ranking criteria were used to develop a ranking order for threats within the ecosystem components. Threat ratings were synthesized among the components for the integrated analysis step. The final threat ranking represented rankings from each of the ecosystem components. This exercise provided a ranking of threats both within components, and an integrated ranking among all components.

Finally, the group developed evaluation criteria to rank a suite of research questions drawing largely on the content and conclusions from the preceding chapters. It should be noted that based on deliberations during this workshop we allowed teams to introduce new, or modify existing research topics from chapters, prior to conducting the ranking excercise. The team decided on four criteria: community concerns, management relevance, cost, and degree of uncertainty. For each criterion except cost, a constructed scale of 1-5 was used for scoring. The team assigned consensus scores for all research questions using these criteria. Additionally, the relevance of each of the research questions to each of the ecosystem components was evaluated and the assessment was used to determine cross-component relevance of each research question by assigning relevance to 1, 2 or 3 components addressed (fish/shellfish, seabirds, marine mammals). At this stage, the cross-component relevance score did not take into account species rankings within the ecosystem components, i.e., species were not assigned different weights based on the ranking they received within each of the ecosystem component teams.

Finally, each research question was assigned a cost category based on the following bins and cost estimate by the expert team for a project addressing the question: Category 1 - <$25,000; Category 2 - $25,000-$50,000; Category 3 - $50,000-$100,000; Category 4 - $100,000-$500,000; Category 5 - > $500,000. This exercise provided a standardized rating of all research questions developed by the ecosystem component teams, and considered their cross-component relevance. The overall step-wise workflow for the SDM process from Module 1 through to Module 3 is presented as Figure 1.

Conclusions and Discussion

The results of the threat assessments for species identified by the fish/shellfish, marine mammals, and seabirds teams relative to climate change drivers are presented as Table 1. These three teams identified several species of particular interest relative to climate change. Given the nature of our process to give more weight topics that would have relevance to communities and managers it is perhaps not surprising that these species are of key economic and subsistence interests in the region.

From the six stressor categories, ocean acidification ranked highest in overall concern for indirect impacts to forage species and to the food chain in the region in general. It was ranked as the #1 threat of concern for marine mammals and seabirds teams and tied for #2 concern with changes in sea ice extent for the fish/shellfish group. Though not explicitly a climate change driver, ocean acidification has connections with climate change. It was included in the SDM process as the climate-related stressor most often identified in the preceding chapters as having an interacting or compounding effect on species and habitats.

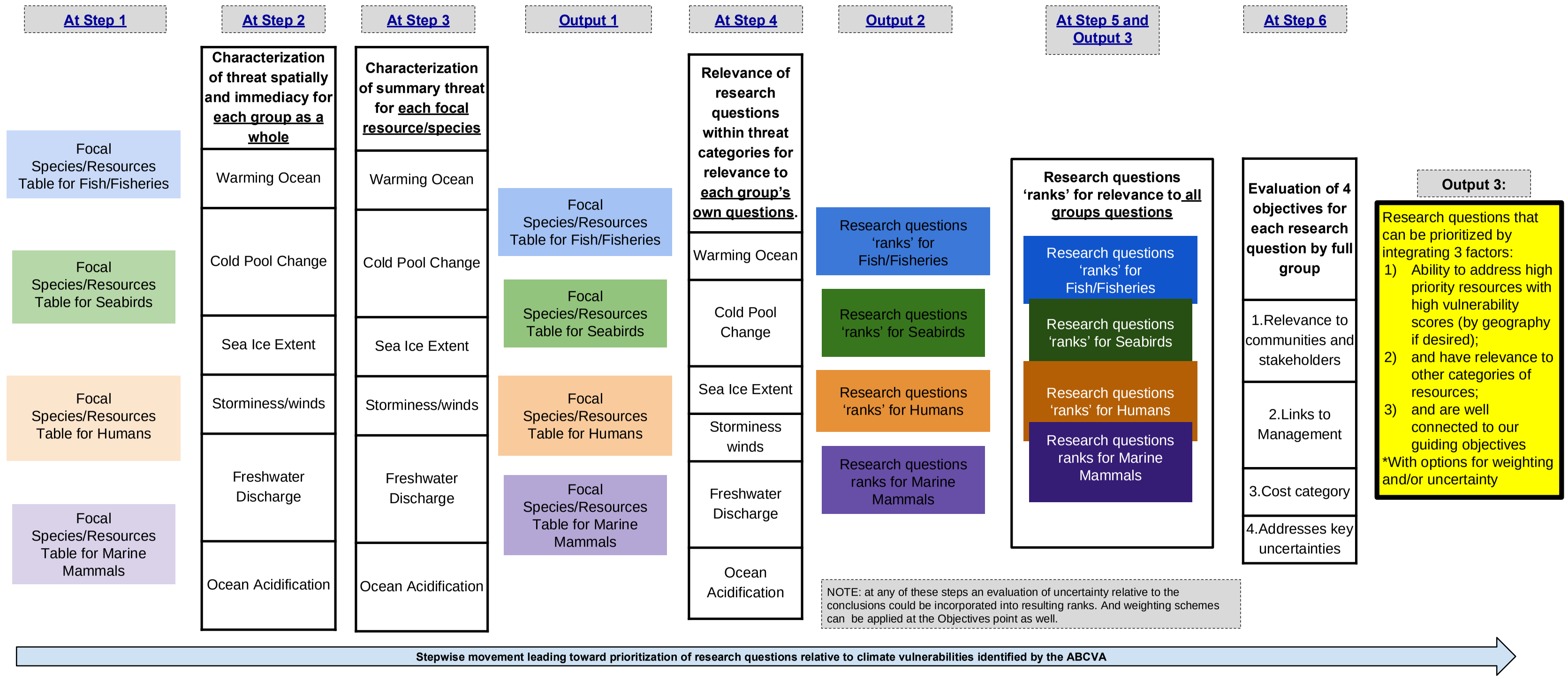


Figure 1. The step-wise Structured Decision Making (SDM) workflow from the four ecosystem component teams as they worked to collectively prioritize research items needed to address climate change vulnerabilities in the Aleutian Islands and Bering Sea.

Table 1. Ranks for species most at risk to climate change relative to climate change drivers in the Aleutians and Bering Sea based on the results of Structured Decision Making (SDM)

1. **Species rankings by ecosystem component, based on equally weighted criteria**
    a. Marine mammals top priority by region
        1. 60 degree north: walrus
        2. 60 degree south: walrus
        3. Aleutians west of samalga pass: sea otter
        4. Aleutians east of samalga pass: sea otter
    b. Seabirds
        1. Diving fish eater, represented by tufted puffin
    c. Fish top priority be region
        1. Nearshore: salmon
        2. Aleutians: atka mackerel, red king crab
        3. North Bering: salmon
        4. South Bering: salmon, pollock
2. **Threat rankings by ecosystem component**
    a. Marine mammals
        1. Ocean Acidification indirect
        2. Sea ice extent direct
        3. Sea ice extent indirect, winds/storminess direct, winds/storminess indirect
    b. Seabirds
        1. Ocean Acidification indirect
        2. Winds/storminess direct
        3. Winds/storminess indirect, cold pool change indirect
    c. Fish/shellfish
        1. Ocean temperature indirect
        2. Sea ice extent direct and indirect, OA direct and indirect
3. **Summary threat ranking**
        1. Ocean Acidification indirect
        2. Sea ice extent direct
        3. Ocean temperature indirect, winds/storminess direct

Table 2 shows the ranking of the 35 research items completed during our SDM process, assigned to bins of three cost categories. The ranks for each of these depictions of our research items range from 1-15, with 1 being of greatest importance and 15 being the lowest. Given the nature of this rapid assessment our team did not attempt to break ties among research items. Similarly, it may not be appropriate to interpret differences between ranks of a point or two as meaning one research item is vastly superior to another. The value that we see in these ranks is that generally identify high, medium and lower priorities among research items.

Further, the topics identified and prioritized by our teams ranged widely in scope from relatively specific questions, like understanding extent of snow cover for ice seal denning, to broader questions about trophic function. We allowed for this flexibility in order to identify a wide range of potential topics that our organizations to consider for potential follow up efforts. To account for this range in scope we organized topics by cost category, so that priorities could be considered based on availability of funding.

We also didn't ask our team to distinguish between on-going efforts vs. new research questions relative to ranking consideration. This allowed for our expert team to assign relative priorities to existing efforts that are thought of as being broadly useful for understanding climate change. For example, the research item of the highest priority was to continue the pollock survey work in the Eastern Bering Sea that is used to develop stock assessments. This NOAA Fisheries led effort has been ongoing for years and from the perspective of our interdisciplinary team has high value to address vulnerabilities related to climate change. Some characterization of new vs. on-going was completed by the team following the ranking process but is not presented in this chapter as inevitably that will change year-to-year based on investments of funding entities in the region.

Our process provides a framework for developing evaluation criteria and synthesizing research recommendations from the preceding chapters in this assessment. Using SDM techniques we were able to rapidly (two days followed by two short meetings) integrate and prioritize recommendations from an interdisciplinary group of scientists that considered utility to managers and interests of stakeholders in the region. Our approach to integrate and prioritize research items offers a template that could be used and applied in other processes for natural resource management. This could range from the development of RFPs by funding entities to longer term science or management plans.

Reflections and Limitations

The 35 questions prioritized in this assessment should be seen as an initial set of research priorities based on the collective work of 30 scientists from a variety of disciplines working in the region. There is certainly a need to revisit these research priorities with regularity, particularly as some of the more easily addressed are pursued and further gaps or complexities are identified. The funding partners of this assessment (ABSI LCC, AOOS, and the Alaska Climate Science Center) aim to build on this work tackling some of these questions together in the immediate coming years. In fact, already the ABSI LCC used the recommendations developed by this expert team to inform a Request for Proposal (RFP) released in February of 2015. When considering the system-wide effects of climate change we had also hoped that this assessment would draw the attention of others conducting and funding science in the region and in 2015 were able to have a number of our higher priority research topics put forward in the North Pacific Research Board's 2016 RFP as well.

With additional time and resources further progress could have been made to identify specific geographic areas of overlapping vulnerabilities for species. For example the work completed in chapter 6 might also be applied to essential fish habitat polygons and marine mammals. Further, that type of exploration could be applied to key seasonal concentration areas for many species groups to look for cumulative vulnerabilities. Locations identified with this heightened level of vulnerability might ultimately serve as index spots where integrated monitoring might detect impacts from climate change.

Ideally our assessment would also have been more comprehensive if we had developed an approach to more synthesize the interactions between stressors. Indeed through the course of this assessment ocean acidification emerged as potentially the greatest threat in the region and yet we were not able to provide our teams with detailed projections to consider. A subsequent effort could be considered that explicitly assesses interactions between climate change and increasingly acidic marine waters that may compound impacts on our species and ecosystem services considered by our expert teams.

The preceding chapter content, expert input gathered in the SDM workshop, our prioritization process and its recommendations for 35 research items offer a foundation for further work in the Aleutians and Bering Sea. We suggest that the highly participatory nature of this assessment is a model that fosters interdisciplinary consideration of science questions relative to management needs. At the outset of this work we knew that a one-year assessment, completed largely by a group volunteering their time, would not develop the final-word on a vast topic like climate change. However, it's our contention that this type of rapid assessment approach *can* begin to narrow what may otherwise be seen as an unmanageable volume of climate and climate-related questions.

Another important aspect of this effort was the attempt to broaden awareness about issues of climate change within the Aleutians and Bering for wide ranging audiences that included regional residents and stakeholders as well as scientists and managers at the local, state and national levels. The editors and chapter authors made presentations a number of venues during the course of the work including:

- Large Landscapes Conference, Washington D.C. in October 2014
- Climate, Conservation, and Community in Alaska and Northwest Canada, Anchorage, AK in November of 2014
- The Alaska Marine Science Symposium, Anchorage, AK in January 2014
- The Pacific Seabird Group's Annual Conference in San Jose, CA in February 2015
- International Association of Landscape Ecology World Congress, Portland Oregon in July of 2015
- American Geophysical Union Annual Meeting (poster), San Francisco, CA in December of 2015.

As described in Box 1.1 we also conducted an interactive climate change town hall in partnership with the Qawalangin Tribe in Unalaska/Dutch Harbor. The session introduced members of this hub community to recent projections about climate drivers in their region and gathered their observations and insights relative to climate change. Paired with that effort in Unalaska a educational curriculum was developed and delivered that drew upon the results of this assessment.

This project resulted in a catalog of online content hosted on the AOOS Arctic Portal where spatially explicit projections for climate drivers are available to view and download. Finally this effort also resulted in the pilot of a downloadable, standalone, 'interactive' that tells the story of this project from motivation to methodology and process through to results, using custom imagery, text, photos, figures and tables.

Acknowledgements

We thank the experts listed in Appendix A for offering their time and insights into the synthesis and ranking process. At the outset of this assessment these same individuals contributed their time toward the development of the preceding chapters and we allowed us to come to them again to help us synthesize those efforts. The leadership and staff from ABSI LCC, AOOS, and the Alaska Climate Science Center are extremely grateful for their commitment throughout the process of this assessment.

Citations

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Table 2. Integrated ABCVA Research Priority Ranking and Cost Category Assignment, Based on Expert Input at ABCVA SDM Workshop December 2014

Research Priority	**Rank**	**Cost category**
Continue to survey eastern Bering Sea pollock stock and ocean conditions and additional research to understand pollock distribution.	1	>500K
Monitoring of pH and aragonite and calcite saturation conditions with respect to ocean currents and productivity. Further studies of response of affected species (e.g., crab, bivalves) to low pH. Further studies of habitat impacts from acidified ocean water.	1	>500K
Modeling of expected sea ice thickness and snow depth, both seasonally and spatially, to evaluate changes in distribution based on key thresholds and define where pupping may no longer be possible based on sea ice monitoring to detect if ice seals start to begin pupping on land.	1	100-500K

Understanding scenarios of shipping traffic that might result in additional potential stress to marine mammal and seabirds species and human communities either due to oil spills, noise, collisions and understand potential changes to seasonal concentration areas for key species and human activities that might increase risk to vessel traffic and development activity.	2	100-500K
Explore shift in distribution and timing of primary and secondary productivity in areas important to marine mammals that are expected to have limited mobility and/or critical seasons—including insights from previous or anticipated cold pool dynamics.	3	<100K
An understanding of clear climatic thresholds for spread of pathogens that could inform regular testing /monitoring of subsistence foods (e.g., PSP in shellfish).	4	<100K
Develop baseline data layers necessary for coastal cultural sites--infrastructure (past and present) and existing rates of change at indicator coastlines to conduct assessments of exposure in hind cast type environments and/or spatially explicitly projected changes in storminess.	4	<100K
Baseline survey to assess cultural site conditions and somehow prioritize sites for mitigation.	4	<100K
Need survey data for body condition like bioenergetic condition of young of the year.	5	<100K
Need to understand advection of snow crab larvae to nursery grounds with shifts in adult population using models and existing data.	6	<100K
Need to understand cues for larval hatching and relationship of spring bloom to sea ice and stratification as mechanisms to explain variability in snow crab recruitment.	6	<100K
Invest in research to establish a baseline for consumption of subsistence species in order to evaluate changes (ie., adaptation)over time.	6	>500K
Census polynyas of north Bering Sea in spring using ships of opportunity and drones to identify habitat characteristics of these sites and distribution and abundance.	6	100-500K
Synthesize available climate information to project storminess levels at specific rookeries and monitoring of effects of storms at rookeries.	6	100-500K
Integrate projections from coupled ocean/climate models (e.g. the PMEL models) especially relative to: nutrient phytoplankton-zooplankton variables and individual-based population dynamics models (e.g. Leslie matrices) for various bird species to explore climate effects, including consideration of multi-stressor effects of ocean acidification and hypoxia.	7	<100K
Develop a quantitative index of the sensitivity of different seabird species to reduced forage abundance, modelled after Furness and Tasker (2000). E.g., seabird body mass, cost of foraging, potential foraging range, ability to dive, amount of 'spare' time in the daily budget, and ability to switch diet.	7	<100K

Expand use of physiological tools which directly relate nutritional stress to population processes (Kitaysky *et al.* 2007, 2010) at large geographical scales at reasonable expense (Satterthwaite *et al.* 2012, Dorrensteijn *et al.* 2012) e.g. measurements of the stress hormone corticosterone (Barbraud *et al.* 2012).	7	100-500K
Explore ~40 year shift in distribution and timing of primary and secondary productivity for essential fish habitat polygons especially those tied to specific physiography or currents that might not allow these areas to shift along with climate—including insights from previous or anticipated cold pool dynamics.	7	<100K
Monitoring of pH and aragonite and calcite saturation conditions with respect to saturation horizons. Studies are needed on species' responses to lower pH.	7	>500K
Monitor changes in seasonality of movements of key harvested species (particularly for northern communities in the region).	7	100-500K
An evaluation of sea surface temperatures via hindcast compared to maritime seabird colony data and/or at-sea to identify potential correlations—perhaps looking for correlations with sea surface temperature anomalies in the region's climate record.	8	<100K
Develop population dynamics models to integrate changes in habitat and food resources (per predictive demographic framework- see above) to articulate (mathematically) mechanisms of change. Subsequently, compare and verify using empirical data (Jenouvrier *et al.* 2009, Wolf *et al.* 2010).	8	<100K
Continue to collect information about the demography, and begin work on genetics and connectivity (dispersal statistics) of seabird populations. As shown by Sandvik *et al.* (2012). Fecundity and survival need to be measured simultaneously with concurrent measurements of the physical and biological environment.	8	100-500K
Monitoring prey distribution and foraging patterns of mammals (for example, bioenergetics model).	8	>500K
Expand COASST monitoring near selected sites and communities to establish baseline information on mortality and capture unusual mortality events.	8	<100K
Describe phytoplankton and zooplankton species composition during windy and calm spring periods. Estimate impacts of species composition on early life survival (e.g., red king crab may need some Thysanoessa for a healthy diet).	9	100-500K
Food web implications (especially for juvenile pollock) by doing additional analysis of existing data.	10	100-500K
Physiological studies to understand conditions for reproduction, growth and survival of Groundfish including development of spatially explicit models of predator-prey dynamics.	11	100-500K
Need for studies of herring overwintering locations and oceanographic conditions.	11	>500K

Explore correlations between breeding success and weather events using Alaska Maritime Refuge monitoring data and hindcast projections of storminess and/or weather observations from sites.	11	<100K
Analyze fall distribution and abundance of seabirds with respect to physical and biological characteristics of fall oceanographic conditions using existing data.	12	<100K
Identify seabird species and sites most at risk to impacts on breeding habitat due to coastal erosion and flooding.	12	<100K
1st- genetic markers and tags for fish stocks to understand intra-species linkages 2nd- investigate potential climate mediated mechanisms for these differences.	13	<100K
Meta-analysis of existing gut content surveys (collected by NOAA) to understand climatological drivers of substitutions occurring in warm vs cold years (noting bycatch data could be really useful info for predator species).	14	<100K
Regular surveys of fish and shellfish in the Northern Bering Sea in consideration of physiological constraints to reproduction.	15	>500K

Appendix A. ABCVA SDM Workshop Participants

Nick	Bond	NOAA, UW-JISAO
Debbie	Corbett	former USFWS
Carol	Fairfield	Alaska OCS Region, BOEM
Kathy	Kuletz	USFWS- Migratory Bird Management
Liza	Mack	UAF
Jim	McCracken	USFWS- Marine Mammal Management
Phil	Mundy	NOAA- Alaska Fisheries Science Center
Lori	Polasek	UAF/Alaska SeaLife Center
Julie	Raymond-Yakobian	Kawerak
Chris	Siddon	ADF&G- Division of Commercial Fisheries
Andrew	Trites	University of British Columbia
Jeff	Williams	USFWS- Alaska Maritime National Wildlife Refuge
Tuula	Hollmén	Alaska SeaLife Center
Jeremy	Littell	Alaska Climate Science Center
Aaron	Poe	Aleutian and Bering Sea Islands LCC
Ellen	Tyler	AOOS
Tom	Van Pelt	AOOS

Appendix B. ABCVA SDM Workshop Agenda

Addressing Climate Change Vulnerabilities in the Aleutian and Bering Sea Islands: using structured decision analysis to prioritize research based on expert and community stakeholder input

Expert Workshop Agenda Dec 10-11, 2014

Wednesday Dec 10

1:00-1:30 pm	Introduction: Status of ABCVA and workshop goals
1:30-2:00 pm	SDM workshop objectives: Introduction to SDM, ABCVA decision context, review of process and workshop sessions
2:00-2:15 pm	Review of breakout session objectives and exercises
2:15-4:30 pm	**Breakout session: Structuring priorities within ecosystem component teams (species, threats, uncertainties)**
	Going backwards – deconstruct and reconstruct recommendations by species and threats
	Build a series of consequence tables 1-3 linking objectives with alternatives (species/resources, threats)
4:30-5:00 pm	Wrap up Day 1

Thursday Dec 11

8:30-9:45 am	Review of Day 1: Priorities from ecosystem component teams
	Insights from Day 1 consequence tables
	Review tables, combine evaluation criteria, standardize scales
	Review synthesis table/clarify and revise cell entries
9:45-10:00 am	Break
10:00-11:00 am	Cost and feasibility objectives
	Develop method to estimate cost
	Define short term/long term/ongoing categories

	Develop criteria to analyze feasibility of research
11:00-12:00 am	Links to management objectives
	Identify management links
12:00-1:00 pm	Lunch
1:00-3:00 pm	Integrating priorities among ecosystem component teams
3:00-3:15 pm	Break
3:15-4:00 pm	Community input and outreach
4:00-5:00 pm	Wrap up and next steps

Overall Appendix A: Aleutian and Bering Sea Vegetation-- Assessment of Status and Potential Vulnerability to Climate Change

Matthew L. Carlson[1,], Jeremey Littell[2], John Walsh[3]

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The Aleutian and Bering Sea islands represent an important repository of unique terrestrial biodiversity. The region is well-recognized as an original source of many surviving populations of arctic and boreal plant species that occupied the unglaciated subcontinent of Beringia (Hultén 1937, Hopkins 1982, Abbott and Brochmann 2003, *Others*, DeChaine *et al.* 2013?-*check*). The terrestrial link to Asia, coupled with isolation from the rest of North America by extensive ice sheets, significantly contributes to the high proportion of plant species with primarily Asiatic distributions and high vascular plant diversity in southwestern Alaska (Hultén 1937, Murray 1997, Carlson *et al.* 2013). Indeed, the present long arc of islands from the Alaskan Peninsula to Kamchatka was a much more continuous landmass with only a handful of larger oceanic barriers (*Citation*), allowing less restricted movement of species in both directions. The Aleutian Islands to Commander Islands has been described as a "two-way filter bridge", regulating the flow of species from both continents (Carlquist 1965), with a progressive decline in Asiatic species from the western to eastern Aleutians (Hultén 1960, Lindroth 1963, Talbot *et al.* 2010). Isolation of presumably more contiguous populations has occurred, following the most recent submersion of the Beringian Shelf approximately 6,000 years BP.

The Aleutian and Bering Sea Islands harbor approximately 25% of the globally rare to imperiled plant species in the state; a very high percent relative to the small land mass (Carlson *et al.* 2007, AKNHP 2014). *Artemisia aleutica*, *Artemisia globularia* var. *lutea, Cerastium aleuticum*, *Draba aleutica*, *Polystichum aleuticum*, and *Veronica grandiflora* are taxa that are endemic to, or are almost entirely restricted to Aleutian and Bering Sea Islands. Additionally, plant taxa such as *Campanula auriculata, Claytonia arctica, Eritrichium villosum*, *Platanthera tulipoides* var. *beringianum*, *Primula cuneifolia* ssp. *cuneifolia*, and *Senecio cannabifolius* represent species that, while reasonably widespread in eastern Asia, have their eastern-most populations restricted to Aleutian Bering Sea Islands.

Globally, island flora and fauna face the highest rates of extinction, where 80% of all recorded extinctions are from islands (*citation*). Island populations tend to be small, geographically restricted, vulnerable to establishment of invasive species, subjected to higher rates of inbreeding, and lack effective dispersal corridors to track suitable ecological niche space through time. These conditions therefore lead to high vulnerabilities of terrestrial island biota, particularly when coupled with habitat conversion, harvest, or other anthropogenic activities. The native biota of the Aleutian Bering Sea Islands is likely less vulnerable than island biotas of lower latitudes. Humans have been present in the region for many thousands of years without apparently causing extinctions, potentially due to a highly generalist and prey-switching behaviors and prey populations dwindled, at least for some human populations (Dunne 2012). While villages are present on many of the larger islands, overall population size is relatively low and the majority of islands are rugged and not inhabited. Increases in human population, commerce, tourism, and shipping, however could pose future conservation risks to the unique flora.

The vegetation communities are variable, ranging from estuarine and beach meadows to peatlands, and to lichen barrens and ericaceous shrub tundra (for complete descriptions of communities see Kindschy and O'Connell 1959, Shacklette *et al.* 1969, Hein 1976, Talbot and Talbot 1994, Talbot *et al.* 1995, Daniëls *et al.* 1998, Daniëls *et al.* 2004, Talbot *et al.* 2005, Talbot *et al.* 2006, Talbot *et al.* 2010, Boggs and Boucher 2013). The absence of trees is the most notable element of the regions vegetation. Attempts have been made to establish forests or tree plantations in the Aleutians that were largely ineffective. Sitka spruce was planted by Russians in the 1800s on Unalaska and adjacent islands and thousands of seedlings were transplanted to the islands following World War II (Alden and Bruce 1989). Spruce plantations persist in protected areas of Expedition Island and Amaknak Island in Unalaska Bay. While strong winds and short growing seasons are clearly a significant factor in tree growth and survival, soil frost heaving on Adak is implicated as the primary cause of spruce seedling mortality in former afforestation efforts (Alden and Loopstra 1986). Taller willow thickets are not uncommon in sheltered areas of the eastern Aleutians to Alaska Peninsula (Talbot *et al.* 2010) and in sheltered creeks on Nunivak Island (*Ref* – Carlson and Boggs per obs.), but are absent in the western Aleutians. Similarly, alder thickets are common in Kamchatka and the Alaska Peninsula, but are lacking or very restricted in the Aleutians and Bering Sea Islands. Any changes that alter the abundance and distribution of large woody species is likely to generate cascading changes to plants and other organisms.

Permafrost is rare in the Aleutian Islands, but common on Nunivak and St. Lawrence Islands, where impermeable frozen soils retain high soil moisture and support wet-sedge communities. Tussock-tundra is also typically associated with permafrost and is common on either side of the Bering Strait but rare on the Aleutian Bering Sea Islands.

The environmental variables that explain the most variation in vegetation communities within islands typically include: temperature, moisture, elevation, soil pH, Na concentration, and soil organic layers (see Young 1971, Talbot *et al.* 2010). The presence of seabird colonies has been implicated in playing a large role in vegetation communities. Lush forb-graminoid dominated meadows are common on islands with high marine-derived nutrient input from nesting birds, and islands that have a lost nesting seabirds due to introduced foxes are largely nutrient-poor ericaceous shrub tundra dominated (Croll *et al.* 2005).

Vegetation communities are also determined by the potential pool of species. The pool of species and potential for dispersal is limited in many cases. However, much different dispersal dynamics are likely for islands close to larger contiguous landmasses and those with greater association with sea ice, such as St. Lawrence Island - conditions that appear to facilitate dispersal (Abbott and Brochman 2003). Knowledge of the historic and current patterns of plant species migration is largely limited to inference from current species distributions and would benefit from a more comprehensive phytogeographic genetic analysis (e.g., see Alsos *et al.* 2010, Eidesen *et al.* 2013).

Response of the ABSI flora to climate change

Few studies of individual species or plant communities in response to climate change in this region are known to us and represent a notable gap in our understanding. Carlson and Cortés-Burns (2013) modeled current and future (2060) habitat suitability for seven rare Aleutian Island to Gulf of Alaska species and suggest that areas of highest future habitat suitability for this group of species largely overlaps with current distributions, but tends to shift to the east and north, with some declines in the western and southern portion of the species' current ranges. Each species tended to respond differently to the environmental variables. It should be noted that this study was unable to model habitat suitability for the rarest species in the region due to low model performance or unavailability of appropriate spatial data in the western Aleutians. Thus the potential responses of the most vulnerable elements of the ABI flora are unexplored.

Determining the climate and habitat envelopes for island populations is challenging, with presumably limited gene flow among islands, each island population is expected to have a much narrower climatic envelope than the broader network of populations might suggest. Studies examining the pattern of contemporary gene flow and quantitative genetics of climate-relevant traits would be useful in gauging the potential for populations to respond to climatic changes. Are populations able or unable to exchange alleles conferring fitness advantages under changing conditions? Assuming dispersal capacities are highly curtailed, do island populations have the necessary additive genetic variation to evolve in response to the challenge?

The response of vegetation in this region to climate change will likely be highly species-specific, with some species responding positively and other negatively. Studies focusing on the dominant species most likely to generate broader responses by the community, as well as those elements that are most at risk of extirpation are encouraged.

We expect that most changes in plant communities will be driven by indirect interactions, such as changes in nutrient availability, competition, herbivory, disease, or alterations to the abundance of mutualists, rather than direct impacts of climate. Direct responses to climate, however, are most likely to be mediated through a range of factors including: increased growing season length, warmer maximum and minimum temperatures, alterations in the magnitude and timing of precipitation, alterations to snow depth, and changes in wind patterns. More specifically, changes in plant community composition may be most obvious where permafrost is lost, where changes in freeze-thaw cycles during shoulder season is most dramatic, and where the season of sea-ice changes most. Additionally, we expect plant communities to change in response to alterations to wind intensity and direction and where sea-level changes inundate tidal meadows and beach communities. Last, while the region experiences relatively high annual precipitation currently, if increases future temperatures are also associated with stable or decreasing precipitation, it is possible for some plant communities, particularly on well-drained substrates, to be exposed to drought stress. Understanding of the baseline primary direct and indirect relationships of dominant species with climate variables would aid in generating more informed hypotheses of future community change.

While climate change is undoubtedly affecting plant populations in the Bering Sea region and will likely exert considerable influence over the future composition of the flora, we should not ignore the potential impacts of non-native species. Non-native ungulates such as reindeer, caribou, cattle, and bison, have been introduced to many of the islands and are well documented to cause significant changes to the flora (*Refs*.). Reindeer populations grew exponentially on St. Matthews Island, reaching densities of 47 per square mile before crashing after destroying their lichen forage and experiencing a winter with high snowfall (Klein 1968). Efforts to reduce or eliminate introduced reindeer and caribou populations from USFWS Maritime Refuge lands are currently underway. Cattle on Chernubura, Caton, and Simeonof islands have caused intensive erosion and even threaten archaeological sites. Additionally, non-native predators can have indirect impacts on the plant communities by changing nutrient dynamics due to losses of seabird colonies (Croll *et al.* 2003). Last, open grassland habitats, particularly under warmer climate scenarios, are vulnerable to non-native plant establishment. Similar habitats have experienced establishment by the highly invasive orange hawkweed in remote areas of Kodiak Island.