

QUANTIFYING TEMPORAL AND SPATIAL ECOSYSTEM VARIABILITY ACROSS THE NORTHERN GULF OF ALASKA TO UNDERSTAND MECHANISMS OF CHANGE

SCIENCE SYNTHESIS REPORT FOR THE GULF WATCH ALASKA PROGRAM

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EXXON VALDEZ OIL SPILL TRUSTEE COUNCIL

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TABLE OF CONTENTS

Table of Contents	ii
Executive Summary	v
Summary of Key Findings	vi
Use of Gulf Watch Alaska Data For Resource Management	viii
Overall Program Recommendations	x
Chapter 1 Program Introduction and Background	1
Chapter Overview	1
Historical context	1
Current Hypotheses for Gulf of Alaska Ecosystem Dynamics.....	3
The EVOS-affected Region	5
Gulf Watch Alaska: Consortium-based Monitoring	6
Addressing Management Needs and Research Questions	10
Moving Forward: Future Vision for the Gulf Watch Alaska program	14
References	15
Chapter 2 Environmental Drivers: Regional Variability in Oceanographic Patterns Across the Gulf of Alaska.	2—1
Research Summary: Long-term Monitoring of Oceanographic Conditions in the Alaska Coastal Current from Hydrographic Station GAK 1	2—12
The Seward Line: 17 years of pattern and variability in the coastal Gulf of Alaska.	2—20
Linking Variability in Oceanographic Patterns Between Nearshore and Shelf Waters Across the Gulf of Alaska.....	2—25
Research Summary: Interannual variability in lower trophic levels on the Alaskan Shelf	2—37
Research Summary: Hydrographic trends in Prince William Sound, Alaska, 1960-2013.	2—42
Chapter 3 Variability within Pelagic Ecosystems of Prince William Sound.....	3—1
Research Summary: Long-term killer whale monitoring in Prince William Sound/ Kenai Fjords .	3—11
Research Summary: Long-term Monitoring of Humpback Whale Predation on Pacific Herring....	3—21

Forage Fish Populations in Prince William Sound: Designing Efficient Monitoring Techniques to Detect Change	3—34
Spatial and Temporal Variation in Marine Birds in the Northern Gulf of Alaska: The Value of Marine Bird Monitoring within Gulf Watch Alaska.....	3—47
Nearshore Marine Bird Surveys: data synthesis, analysis and recommendations for sampling frequency and intensity to detect population trends	3—53
Research Summary: Temporal change in a subarctic marine bird community linked to habitat and climate change.....	3—61
Research Summary: Long-term monitoring of seabird abundance and habitat associations during late fall and winter in Prince William Sound	3—70
Chapter 3-Appendix 1: Summary of marine birds projects in the Gulf Watch Alaska region .	3—79
Chapter 4 Variability within Nearshore Ecosystems of the Gulf of Alaska	4—1
Research Summary: Project Summary: Influence of static habitat attributes on local and regional biological variability in rocky intertidal communities of the northern Gulf of Alaska.....	4—8
Pacific blue mussel (<i>Mytilus trossulus</i>) Abundance in the Gulf of Alaska: synthesis of gulf watch data (2006-2013) and a Consideration of Major Recruitment events (1989-2013).....	4—16
Chapter 5 Lingering Oil Monitoring	5—1
Timelines and Mechanisms of Wildlife Population Recovery Following the <i>Exxon Valdez</i> Oil Spill.	5—6
Chapter 6 Conceptual Models	6—1
Conceptual Model Development.....	6—1
General Ecosystem Model.....	6—1
Sub-Models.....	6—2
Management-linked sub-models and decision support tools.....	6—6
Chapter 7 Program Summary and Recommendations	7—1
Monitoring Highlights and Ecological Significance.....	7—1
Environmental Drivers.....	7—1
Pelagic Ecosystems	7—2
Nearshore Ecosystems.....	7—2

Recommendations for future work..... 7—3

 Overall Program Recommendations 7—3

 Environmental Drivers Component 7—5

 Pelagic Ecosystems Component..... 7—5

 Nearshore Ecosystems Component..... 7—6

 Lingering Oil Component 7—6

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EXECUTIVE SUMMARY

The northern Gulf of Alaska (GOA) is a vast, dynamic area that contains some of the most productive, diverse, and unique marine ecosystems in the world. This area supports numerous coastal communities with economies that include commercial and recreational fishing, tourism, and subsistence food production. Several large-scale perturbations have strongly impacted the ecology over the region in the past century including the 1964 earthquake, the 1989 *Exxon Valdez* oil spill, various volcanic eruptions, and a variety of anthropogenic effects such as targeted fish harvest and supplementation efforts. Pronounced marine ecosystem “regime shifts” have also occurred in the GOA, most notably an abrupt shift in the late 1970s. Future climate changes are anticipated to modify environmental conditions that will continue to affect the ecology of these ecosystems.

Gulf Watch Alaska is an integrated ecosystem monitoring program funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) that began in 2012 in parallel with the EVOSTC Herring Research and Monitoring Program. The two programs work collaboratively to provide long-term monitoring data regarding status of environmental drivers and the pelagic and nearshore ecosystems of the northern Gulf of Alaska marine environments. These data can be used by managers to further inform resource conservation programs as well as aid in management of species injured by the *Exxon Valdez* oil spill. Both programs take advantage of the information and expertise provided by the extensive monitoring work conducted in the region thus far through EVOSTC-funded projects as well as from other sources. The Gulf Watch Alaska program conducts monitoring within multidisciplinary components, with the overall objective of collecting and analyzing information, making it available to resource managers and the public and assessing it holistically to understand the range and interaction of factors affecting individual species and the ecosystem. Both programs were funded under 5-year funding cycles with the intent of maintaining a 20-year monitoring effort. These long-term monitoring efforts and the resulting time series data will provide critical information on the response of these ecosystems to climate change and their recovery from previous perturbations, especially the *Exxon Valdez* oil spill, as well as provide data to assess ecosystem response under potential future conditions.

This report presents the first steps toward an interdisciplinary synthesis of EVOSTC-funded data, including previously gathered historic data and the two to three years of information collected under the current Gulf Watch Alaska program, supplemented by data from other studies. We do not report on all agency or partner process and monitoring studies that are leveraged through the collaborations afforded under the two EVOSTC funded monitoring and research programs. The purpose of this report is to inform stakeholders of the current state of knowledge on the interplay of the ecosystem components within the region, using results from selected Gulf Watch Alaska monitoring efforts. The report will provide a basis for continued integration efforts with the Herring Research and Monitoring program and for planning ongoing monitoring programs.

The first chapter of the report provides background information on the region, previous monitoring efforts and the structure of the Gulf Watch Alaska ecosystem monitoring program. The core monitoring results are presented in four chapters, covering each of the program components: Environmental Drivers (Chapter 2); Pelagic Ecosystems (Chapter 3); Nearshore Ecosystems (Chapter 4); and Lingering Oil (Chapter 5). These component chapters each contain an introduction that summarizes overall monitoring results within the component and individual articles that provide more detail on selected topics. The sixth chapter provides a description of the conceptual models being developed across all program components. The seventh chapter contains a summary of current science findings and recommendations developed by the entire team to improve the Gulf Watch Alaska program and help inform planning for the second five years of the EVOSTC ecosystem monitoring program.

SUMMARY OF KEY FINDINGS

The Gulf of Alaska (GOA) has paths of energy transport through two distinct, but connected food webs: a pelagic, offshore environment with most primary production from phytoplankton and a nearshore environment with primary production from macroalgae, phytoplankton and benthic microalgae. Both food webs are driven by environmental conditions, including temperature, salinity, nutrient supply, and solar radiation, that control primary production and biological processes at higher trophic levels. In this section, we describe the key findings and the ecological significance of those results within each of the four program components.

Environmental Drivers Component

The Gulf Watch Alaska program scientists conduct monitoring of environmental conditions across the EVOS-affected region to characterize the temporal and spatial patterns in marine conditions that may drive biological processes and ecosystem structure. Oceanography and plankton monitoring is conducted across the GOA shelf at the GAK1 mooring and Seward Line, and within Prince William Sound (PWS) and lower Cook Inlet. Continuous Plankton Recorder (CPR) data are also collected on cargo ships that run from Cook Inlet to Puget Sound. The sampling design sustains long time series measurements on the shelf and provides data to assess linkages between nearshore estuary and shelf conditions. Chapter 2 describes results from some of the long-term oceanography and plankton observations, with monitoring highlights and broad ecosystem implications summarized below.

Our data collected during oceanographic monitoring at GAK 1 from 1970 to present provides evidence for several long-term trends on the GOA shelf over that period, including: 1) an overall warming of shelf water (of nearly 0.8 °C in the upper 100 m over 40 years), with intermittent periods of cooler temperatures; 2) an increase in salinities in deeper waters (> 100 m); 3) a decrease in upper ocean (0 –

100 m) salinities; and 4) increasing stratification. The upper ocean salinity decrease is in agreement with the long-term trend toward increasing freshwater discharge throughout the GOA. Data consolidation efforts within PWS show similar thermal trends on the shelf, but opposite ones inside PWS driven by increased glacial melt. These long-term trends have biological implications as a warming environment should affect the metabolic activities of a host of marine species. The increase in stratification appears to be a response to surface freshening due to increased coastal freshwater discharge, a reduction in wind mixing, and an increase in deep salinity on the shelf; however, the reasons for the deep salinity increase are uncertain. Stratification changes have implications for the magnitude, timing and duration of spring primary production and how that productivity may be reflected in upper trophic levels. These changes have important implications on nutrient availability, ocean acidification, and biological production at all trophic levels through bottom-up forcing.

Regional variability in environmental conditions

While coherent patterns in temperature and salinity time series are observed at seasonal, interannual and decadal time scales within the northern GOA, there is considerable regional variability in environmental conditions at shorter time scales. This variability will also drive spatial differences in species that respond at shorter time scales and raises questions on the space and time scales at which environmental conditions should be monitored to assess linkages to lower trophic levels and subsequent impacts at higher trophic levels. We expect that this may be especially important to understand ecosystem response in years with atypical environmental conditions, such as the unusually warm ocean conditions that started in late 2013 in the Gulf of Alaska and which are part of a warm temperature anomaly across the north Pacific Ocean and into the Bering Sea. The CPR and Seward Line data show that there is strong evidence of bottom-up forcing. Phytoplankton and zooplankton abundance, timing, and composition are all influenced by the physical environment. Strong interannual variability in physical variables and the plankton, even between adjacent years, is clearly evident. Interannual variability in plankton abundance is much greater than trends in abundance across the time series.

Pelagic Ecosystems Component

Long-term, integrated ecological monitoring provides critical information needed by managers in the context of a constantly changing environment. Multiple publications are summarized in Chapter 4 of this report that detail some aspects of our monitoring efforts. Key findings include:

Killer whales – Trajectories of three populations of killer whales demonstrate differing sensitivities to perturbations in this long-lived species. We do not yet know the long-term consequences of EVOS for the declining population (one resident AB pod) that may range from eventual recovery to possible extinction. We note the great value in these data as this is one of the only projects with data collected prior to EVOS.

Humpback whales – Recent removals of herring in PWS by humpback whales approximated the biomass equivalent of the most recent herring fishery harvest (1998). A hotspot (area of consistently high seasonal species aggregations) has been identified in Montague Strait where an influx of whales has been documented in fall and winter as they follow herring. Humpback whale predation in PWS can exert top-down controlling pressure on herring, including competition with fish-eating marine birds and other marine mammals for food, but this may change as prey fields change.

Forage fish – Efforts over the past two decades to document the distribution and abundance of forage fish in PWS and surrounding areas were reviewed. Drawing from these studies, and considering the range of

life histories encountered among species of forage fish, a variety of methods were tested and refined into a few efficient procedures for long-term monitoring of multiple species. Some of these methods were developed in mutually beneficial collaborations with other pelagic component studies (e.g., herring, humpback whale, and marine bird surveys).

Marine birds – The strongest spatial pattern of summer marine bird community composition in PWS was related to water depth and distance from shore, paralleling the nearshore-pelagic structure of the marine food web. In PWS, post-spill summer population trends of most offshore birds declined dramatically while most nearshore populations remained relatively stable or increased. This pattern of community change is indicative of changes in the pelagic prey base. Densities of the most abundant marine birds in PWS varied significantly between early and late winter, suggesting multiple surveys are required to quantify the distribution and abundance of wintering populations.

Nearshore Ecosystems Component

The value of nearshore monitoring is illustrated by two detailed syntheses reported in this document. In the first example, rocky intertidal community structure was found to be driven largely by regional differences and tidal elevation, with minor effects of static attributes (Konar et al., this report). This analysis provides perspective for framing future analyses of dynamic environmental drivers. This analysis will allow us to account for variability related to these static attributes in future analyses of dynamic environmental drivers. In the second example, over the period from 2007 to 2013, we have observed a significant reduction in mussel abundance across the Gulf of Alaska (Monson et al., this report). That decline in mussels correlates with changes in sea otter and black oystercatcher diets. Further, the geographic scope of synchronous mussel abundance changes suggests they may reflect changes in the pelagic environment.

In addition to the examples of key findings described above, we continue to collect data on a wide variety of nearshore ecosystem metrics that allow us to address numerous questions. We have observed stable or increasing sea otter abundance in all of our sites since 2007. Also, we have not detected changes in abundance of black oystercatchers or other marine birds over that same time period. There have been notable changes in several intertidal invertebrates and algae, including declines in abundance of several bivalves across the Gulf of Alaska. We looked for, but did not detect, evidence of sea star wasting disease in the north Gulf of Alaska through 2014, in contrast to infected areas further south. Baselines for contaminants in mussel tissues have been established. Data gathered and compiled from all of these studies illustrate how environmental shifts can alter nearshore communities, consequently impacting species of focus for conservation and management programs.

Lingering Oil Component

Effects of the *Exxon Valdez* oil spill on some vulnerable wildlife, particularly sea otters and harlequin ducks, were observed for more than two decades. Recent findings indicate that effects of lingering oil on these species are no longer detectable and population status is consistent with recovery as defined by the EVOSTC. However, some oil is known to remain in the environment, although the exact amount is uncertain.

USE OF GULF WATCH ALASKA DATA FOR RESOURCE MANAGEMENT

A key goal of the Gulf Watch Alaska program is not only to maintain a robust collection of ecosystem data, but also to ensure that the key findings inform real-time management needs and applications. We are tracking management use of data as one measure of program success. The following examples illustrate how Gulf Watch Alaska data are being used by federal, state and tribal agencies, as well as the public:

- Oceanography, plankton and humpback whale monitoring data collected in the Gulf Watch Alaska program are being used by the Herring Research and Monitoring program investigators and the Alaska Department of Fish and Game to improve herring stock assessment models.
- Killer whale monitoring data is used in NMFS killer whale stock assessment reports for marine mammal species in Alaska
- Killer whale identification catalogues, guidance, and other data products are used by the tour boat industry in Kenai Fjords National Park, Prince William Sound, and Kachemak Bay.
- Humpback whale population and habitat use information are provided to the NOAA NMFS Protected Resources Division for evaluation of changes to the species listing under the Endangered Species Act. Humpback whales are currently listed as endangered throughout their range, but two populations (Central North Pacific and North Pacific) are under NMFS review for delisting. The Gulf Watch Alaska data will be part of a limited dataset available on humpback whales in Alaska to assess listing status and, if delisted, whale status during the five-year post delisting review period.
- The states of Alaska and Hawaii used humpback whale monitoring results from the Gulf Watch Alaska program in petitions to delist humpback whales from the Endangered Species List in US waters.
- Under new interagency agreements, oceanography, marine bird and marine mammal observations in lower Cook Inlet will be provided to the Bureau of Ocean Energy Management (BOEM) to inform their environmental assessment for anticipated Cook Inlet oil and gas lease sales. BOEM is providing additional support to sustain quarterly Cook Inlet shipboard surveys and marine bird observations.
- Seasonal distribution patterns and trends in marine birds detected in the PWS, Seward Line, and Cook Inlet surveys are used by USFWS to inform management approaches for priority species.
- Seabird and whale data are used by Ship Escort/Response Vessel System (SERVS) and other oil spill response training and contingency planning organizations (PWS and Cook Inlet Regional Citizens Advisory Councils, NOAA Office of Response and Restoration, Oil Spill Recovery Institute).
- The marine bird survey data (PWS, Seward Line, Cook Inlet) are archived in the North Pacific Pelagic Seabird Database, which has multiple applications in management and conservation actions.
- Sea otter monitoring data are used in USFWS sea otter stock assessment reports for marine mammal species in Alaska and are available for use in management and conservation by state and tribal governments.
- The nearshore component has accumulated baseline data on important nearshore species that previously did not exist for areas across the GOA. These data are available for management and conservation purposes, including risk assessment and remediation in the event of future perturbations. For example, during the eruption of Mt. Redoubt in 2009, nearshore data were used

to highlight areas along the coastline that were considered high priority for protection (booms) in the event of a spill from the Drift River terminal oil storage tanks..

- Nearshore baseline data will be used to inform development of BOEM's environmental assessment for lower Cook Inlet oil and gas lease sales.
- Nearshore monitoring data are provided to the National Park Service (NPS) at regular intervals to assist managers in a variety of decision-making processes as well as through community outreach and interpretation programs. Specifically, the nearshore data are used to produce the NPS State of the Park Reports. These reports are used by park managers to assess the status of important park resources and determine if changes are needed in future management plans.
- Nearshore monitoring has been able to provide information for emerging high priority management needs, such as monitoring for invasive species from marine debris from Fukushima and documenting that, as of 2014, no sea star wasting disease has been observed in the Gulf Watch Alaska nearshore study areas.
- Marine bird data are provided annually to the USFWS for migratory bird management applications.
- Data from GAK 1 and the Seward line have been used in over 70 scientific investigations addressing topics in physical and biological oceanography relevant to fisheries management (see GAK 1 website: http://www.ims.uaf.edu/GAK_1/ and Seward line: <https://www.sfos.uaf.edu/sewardline/Publications.html> for partial listing of publications).

OVERALL PROGRAM RECOMMENDATIONS

The EVOSTC-funded Gulf Watch Alaska program provides a unique opportunity to collect and integrate ecosystem data and make it available to state and federal resource managers and to the public. The results outlined in this synthesis report confirm the value of these long-term time series data for ongoing management of EVOS-affected species in the face of changing climate conditions. As one example, the program is providing trustee agencies with the ecosystem information needed to assess the impacts of the anomalously warm Pacific Ocean conditions on both managed species and ecosystem function. We recommend that first priority be given to continuing ecosystem monitoring efforts within the GWA program. The analyses conducted for this report, combined with discussions during the joint EVOSTC science workshop with the Herring Research and Monitoring Program, show that these observations are valuable for resource managers. Trustee agencies need both the observations and integration of multi-disciplinary data to assess the long-term effects of the spill and the response of the species to changing environmental conditions. Support for cross-program data integration, in addition to data collection under individual projects, and for robust data management is critical to improve how EVOSTC data are used by resource managers. We also note that monitoring activities, program management and data management services within the Gulf Watch Alaska program are currently highly leveraged with additional agency efforts, which may not be sustained indefinitely.

Efforts that we anticipate could be maintained within current program funding levels

We recommend sustaining long-term monitoring of marine conditions and species in the current program to build baseline data sets that can be used to assess post-spill ecosystem response, characterizing patterns and trends over decadal periods, along the GOA coast and between estuary and shelf environments. These include:

- Sustain current long-term monitoring of marine conditions and targeted species.

- Ensure robust data management services.
- Improve integration of data within *Gulf Watch Alaska*, with Herring Research and Monitoring program, and from other organizations.
- Target synthesis/conceptual modeling to develop decision support tools for improved resource management.
- Maintain outreach to managers, educators, and communities. Develop outreach products including annual “State of the Nearshore” or “Gulf Watch Alaska” reports.
- Maintain data coordination support for both programs.

Improve integration and synthesis through restructuring of currently funded projects. For example:

- Transition forage fish project to forage species monitoring/index development – linked with Herring Research and Monitoring. Improved understanding of bottom-up and top-down (predator diet) processes.
- Continue funding for science synthesis (currently through NCEAS working groups and conceptual modeling projects) through tools such as program post-doc (and graduate student) positions to conduct targeted efforts (also allows mentoring and knowledge transfer).

Projects requiring additional funds that will improve integration

We recommend several projects that will improve integration through analyses and higher-frequency monitoring:

- Provide capacity (staffing) to develop targeted data products and decision support (e.g., State of the GOA report, scenario planning with *Gulf Watch Alaska* time series).
- Establish temporally intensive nearshore/pelagic/environmental drivers monitoring site(s) at accessible locations (e.g. coastal labs) to allow high-frequency sampling throughout the year, including taking advantage of existing monitoring work such as the Middleton Island seabird assessment project.
- Use monitoring data to develop an understanding of important ecological processes and trophic relationships. Suggested mechanisms: collaborations with North Pacific Research Board, Bureau of Ocean Energy Management, or other entities:
 - Example: growth and recruitment of benthic invertebrates and algae, and performance of vertebrate consumers.
- Expand data management collaborations with trustee agency data centers to ensure a long-term (beyond EVOSTC program funding) data archive for EVOSTC-funded ecosystem data.
 - Examples include redundancy in data back-up and documentation of location of various data packages.
 - Streamline processes to facilitate use of national archives/repositories (i.e. National Centers for Environmental Information conversion work in progress, NCEAS)

Projects that will not continue to the future

- Studies evaluating exposure to lingering oil and status of recovery of harlequin ducks and sea otters have concluded as of 2014. Continued monitoring of oil on shorelines is recommended (see below). Note: continued monitoring of other metrics related to sea otters and harlequin ducks is ongoing as part of the Nearshore component, but will not involve captures or biomarker studies to assess exposure.

Chapter 1 PROGRAM INTRODUCTION AND BACKGROUND

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CHAPTER OVERVIEW

The Gulf of Alaska (GOA) in the northeastern Pacific Ocean is considered to be one of the most productive marine ecosystems in the world, with numerous complex interactions and food webs (Spies 2006a). Primary and secondary production (phytoplankton and zooplankton) are considered to be key drivers of the overall ecological productivity and function within the region. These organisms provide for transference of energy from inorganic nutrients, thermal, and ultraviolet energy to useable organic forms of energy that serve as the base for marine food webs, either through direct consumption or intermediaries such as forage fish. The timing and magnitude of primary production is driven by natural physical forces that affect nutrient availability, solar input, and metabolic activity (through thermal variability) both locally and in large regional patterns (Mundy 2005). The northern GOA watersheds, estuaries, and bays are part of a larger, interconnected oceanic system in which these natural physical forces such as currents, upwelling, downwelling, precipitation and runoff, all play important roles in determining regional primary productivity (Mundy 2005, Harwell et al. 2010).

The purpose of this introductory chapter is to provide a framework for the program that illustrates the historical approach with its suite of independent studies and foci that lead to the development of the coordinated parallel programs (Gulf Watch Alaska and the Herring Research and Monitoring Program). Included is a discussion of several key hypotheses developed to explain processes within the Gulf of Alaska (GOA) ecosystems that helped provide the basis of several of the monitoring projects under the Gulf Watch Alaska and Herring programs. Finally, we conclude with a discussion of the possible future direction of the program with the summary and recommendations for future work presented in Chapter 7 of this document.

HISTORICAL CONTEXT

The northern GOA's complex coastal areas and marine environments host a wide variety of organisms that support many of Alaska's coastal human communities. The groundfish fisheries of the northern GOA contributed an estimated \$375 million dollars in gross product value in 2012 (A'mar et al. 2013), while the Cook Inlet driftnet and Prince William Sound purse seine salmon fisheries provided a five-year average of \$61.4 million in real gross earnings to permitted commercial fishers from 2007-2011 (Shriver 2012). Tourism in these areas also plays a large role in the economies of the coastal communities of the GOA, home to six U.S. National Parks, the Alaska Maritime National Wildlife Refuge, and numerous Alaska State Parks and recreational areas. Charter fishing, wildlife and eco-tours, and cruise ships also capitalize on the amazing ecological diversity and productivity of the area.

Several large-scale ecological perturbations have occurred within the northern GOA region over the past century (Figure 1-1). In March, 1964, a magnitude 9.2 earthquake shook Southcentral Alaska, causing areas of land to displace as much as 18 meters and areas of uplift as much as 9 meters near the epicenter in Prince William Sound (ADMM 1964). The earthquake killed or injured many residents and caused major structural damage to surrounding areas. Large areas of uplifted terrain from the earthquake elevated nearshore habitats above the intertidal zone, changing these coastal ecosystems. In March of 1989, the

Exxon Valdez oil tanker ran aground on Bligh Reef spilling an estimated 750,000 barrels of crude oil into Prince William Sound. The spill devastated coastal marine habitats and their occupants, as well as the dependent coastal communities of the area, from Cordova to Kodiak. In the 25 years following the *Exxon Valdez* oil spill (EVOS), numerous studies and efforts have been conducted to understand the impacts of the spill on the region and restore injured resources through work funded by the *Exxon Valdez* Oil Spill Trustee Council (Mundy 2005, Spies 2006b, Harwell et al. 2010). As time has progressed, chronic effects directly related to the spill have become more difficult to ascertain due to attenuation of the oil within the environment, changing climate, natural variability, and anthropogenic changes (e.g. fishing and other industrial pressures, pollution with added vessel traffic from maritime commerce and tourism). Long-term observations are fundamental requirements to detect ecological changes due to an oil spill or any other unknown drivers. Only then can we direct our research to understanding the process of change, and ultimately create or refine predictions of future conditions. As recognized in the 1994 EVOS Restoration Plan, effective restoration requires an adaptive management cycle that updates restoration activities as new information and understanding is acquired.

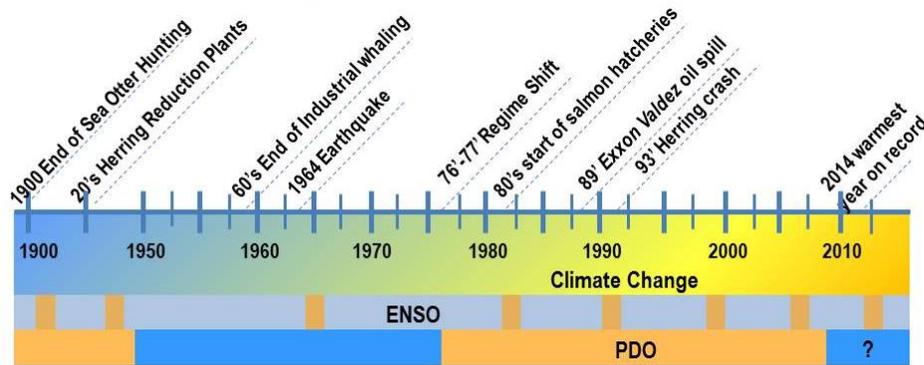


Figure 1-1. Perturbations to the Gulf of Alaska ecosystems in the last century. Variability has occurred due to acute events and longer term chronic cycles such as climate change. The long-term climate cycles include El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Long-term monitoring of key species provides insight into how these perturbations impact the Northern GOA ecosystem.

The productive ecosystems within waters of the northern GOA, lower Cook Inlet, Kodiak, and along the Alaska Peninsula and Aleutian chain were profoundly affected by the EVOS, with impacts that continue, though to a diminished extent, to the present day (Mundy 2005). Since the EVOS, there have been numerous planning efforts to develop a coordinated, long-term monitoring strategy for the oil spill affected area, including: the overall guidance in the 1994 Restoration Plan; the detailed ecosystem monitoring plans of the 2002 Gulf Ecosystem Monitoring and Research Program (GEM); and more specific plans such as the nearshore restoration and ecosystem monitoring plans (Schoch et al. 2002, Dean and Bodkin 2006a). In the Gulf Watch Alaska program, we monitor nearshore and pelagic-based ecosystems in conjunction with measures of physical forcing to better understand the connections between these systems. Long-term monitoring of these ecosystems provides information that can be used to anticipate and respond to changes in the GOA ecosystems for managers within the marine-dependent economies of the region. In the following, we describe several hypotheses for how the GOA ecosystems

function with respect to the architecture of the Gulf Watch Alaska monitoring program and development of future recommendations for the program.

CURRENT HYPOTHESES FOR GULF OF ALASKA ECOSYSTEM DYNAMICS

Several hypotheses have been laid out to describe the mechanisms shaping the structure and affecting the dynamics of the GOA ecosystem or its components (Figure 1-2). Generally, these hypotheses fit into three categories: those involving bottom up processes such as temperature and nutrient availability controlling plankton blooms; those involving top down forcing such as humpback whale predation mediating populations of forage fishes; and those involving processes that control forage fish production and their relationships as both predator and prey within the GOA (Anderson and Piatt 1999, Mundy 2005, Hatch 2013). In this section, we recap these major hypotheses, which involve overlapping themes, but are discussed here separately. These hypotheses offer a background to the synthetic conceptual ecological modeling being conducted by the Gulf Watch Alaska program.

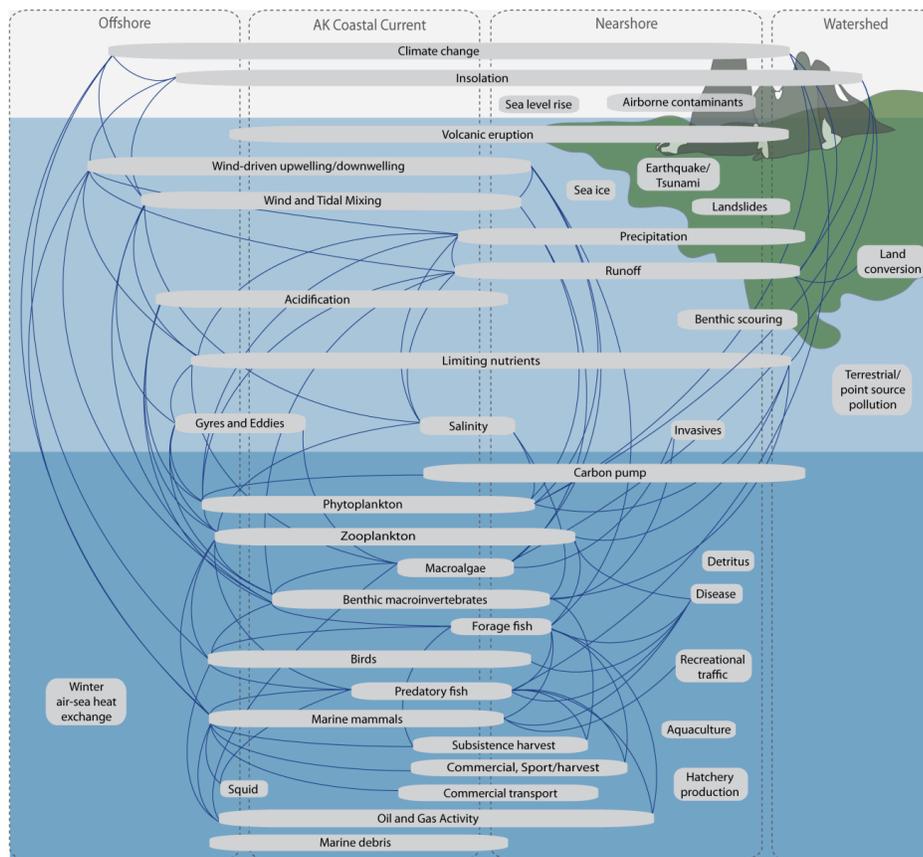


Figure 1-2. Conceptual model illustrating the complexity of numerous ecological linkages within the Gulf of Alaska.

Shelf/Offshelf productivity

The shelf/offshelf productivity hypothesis described in Mundy (2005) incorporates the idea of an optimal stability window that favors either on-shelf or off-shelf production. This idea is based upon observations through the late 1970s-1990s that during conditions of the warm phase of the PDO, environmental conditions favored off-shelf productivity with strong upwelling of deepwater nutrients and a shallow, productive mixed layer. During these conditions, greater precipitation levels in the nearshore and shelf environment resulted in reduced nutrient upwelling, greater freshwater import with strong stratification that reduced mixing, and decreased nearshore production. These conditions are thought to act conversely under the cool phase or lower pressure phase of the PDO.

Match-Mismatch Hypothesis

Our changing climate and resulting changes in environmental conditions are discernible in ocean conditions and corresponding timing of ontogenetic shifts of various species of plankton (Mackas et al. 2007). These shifts have demonstrable effects on higher trophic levels such as salmon and other fishes, that depend on available prey during key phases of development (Beamish and Mahnken 2001, Overland et al. 2010). Coined the match-mismatch hypothesis, the timing of plankton blooms and the corresponding dependence of specific stages of fishes on plankton prey is thought to be one factor controlling species abundance and survival (Durant and Hjermann 2007). Under this hypothesis, species are adapted to the short – and tightly coupled with environmental conditions – seasonal patterns of prey availability. Therefore, anomalous environmental conditions may occur that result in shifts in tightly coupled species abundances or life history timing thereby reducing or eliminating prey available for the next highest trophic level or predator group –a mismatch of timing of species abundances.

Pelagic-Benthic Split Hypothesis

This hypothesis centers on the timing and duration of phytoplankton production as a mechanism for energy transfer to either the pelagic or the benthic components of the marine food web (Eslinger et al. 2001). Work completed in Prince William Sound by Eslinger et al. (2001) suggests that in years when early, strong stratification developed, phytoplankton blooms were short, intense, and had short residence times in surface waters thereby limiting availability to grazers within the pelagic food web. In years where stratification was weaker and slower, phytoplankton blooms were prolonged, providing more energy to grazers and to the pelagic ecosystem.

Optimal Stability Window Hypothesis

The optimal stability hypothesis was proposed to describe the physical environmental drivers of the observed association between Pacific salmon populations and variability in Pacific Ocean pressure systems such as the Aleutian low pressure system (Gargett 1997, Mantua et al. 1997b). Under this hypothesis, phytoplankton production is proposed to be driven primarily by the timing and duration of water column stability during the spring months. The Aleutian low pressure area and strength are implicated as driving water column stability in the North Pacific, and thus primary production –the mechanism for energy transport to higher trophic levels such as fish production. It is suggested that there is an ‘optimal’ window for plankton production that best coincides with the migration timing and nutritional requirements of early marine rearing salmon (and can be extrapolated to other species as well).

Physiological Performance-Temperature Mediated Survival Hypothesis

This hypothesis centers on temperature as the primary mediating factor in abundance of marine species in the GOA. Temperature is, undoubtedly, the primary factor regulating individual metabolic function in most ectotherms, where metabolic processes consume an increasing amount of individual energy budgets as temperature increases. Numerous studies have highlighted the correlation of northern Pacific salmon populations with the Pacific Decadal Oscillation (PDO) index, an index that incorporates the strength of the Aleutian low pressure system with sea surface temperatures as well as relating benthic and pelagic fish species abundances and distribution to this and other thermally derived indices (Hollowed et al. 2001a, Mueter 2002, Rose 2005, Omar I. Abdul-Aziz et al. 2011, Stachura et al. 2014). Mackas et al. (2007) discusses how warm pulses of water impact the life cycle timing, size, and lipid content of dominant copepod species. These changes in copepods (serving as a primary prey item to many species) could also explain the correlation of patterns in abundance in upper trophic levels with indices of temperature. Thermal patterns are strong drivers of species metabolic function and therefore of patterns of abundance and distribution, but other environmental conditions that provide access to nutrients and the route by which nutrients are stored are also key factors to consider (Di Lorenzo et al. 2013).

Food Quality Hypothesis

This hypothesis is intimately tied to the physiological performance hypothesis described above because temperature mediates energy demand through metabolic function- thereby impacting the ability of an organism to acquire, use, and store energy. This then impacts an individual organism's function as both predator and prey. The concept of changing prey quality as a driver for species abundance and distribution is explored in many studies of GOA and western Alaskan ecosystems, notably: Mackas et al (2007) with copepods; Hatch (2013) and Anderson and Piatt (1999) with seabird diets; Springer and van Vliet (2014) with seabird diet and pink salmon abundance.

THE EVOS-AFFECTED REGION

The EVOS affected numerous natural resources across the northern GOA, including in Prince William Sound, lower Cook Inlet, along the Alaska Peninsula, and Kodiak Island (Figure 1-3). The factors and processes that regulate primary production in this region are the drivers of energy conversion to the food webs within the system (Mundy 2005). The physical environment, including topography and geomorphology, plays an important role in regulating oceanic conditions and ecology of the northern GOA. This region is located in the northern Pacific Ocean along the borders of the Pacific and North American tectonic plates and consequently undergoes frequent earthquakes and volcanic eruptions (ADMM 1964, Mundy 2005). The steep, glaciated mountainous terrain that borders the northern GOA creates conditions conducive to strong winds and storm patterns which impact ocean conditions, and sits in close proximity to the steep oceanic shelf break that leads to strong ocean current influences (Mundy 2005, Harwell et al. 2010). The system is strongly mediated by two major ocean currents: the Alaska Coastal Current (ACC), and the stronger, offshore Alaska Current (AC). The interactions between these currents and eddies, in combination with the frequent strong storm events and high precipitation, provide a foundation for a great diversity of habitats with strong seasonal patterns within the GOA (Harwell et al. 2010). The deep off-shelf water is the primary source of nutrients for nearshore algae and plants, making these areas vulnerable to environmental conditions that influence upwelling of nutrients to the shelf (Mundy 2005). The northeastern GOA receives heavy precipitation during the frequent storm events because it is at the end of the Pacific storm track, This leads to strong freshwater influences that can also

impact ocean conditions and availability of nutrients through stratification (Mundy 2005, Harwell et al. 2010). Therefore, localized processes that affect stratification and upwelling, such as variation in precipitation and wind patterns associated with coastal geomorphology and patterns of glaciation, are strong drivers of regional variability in primary and secondary production (Mueter et al. 2002, Ladd 2007, Mackas et al. 2007).

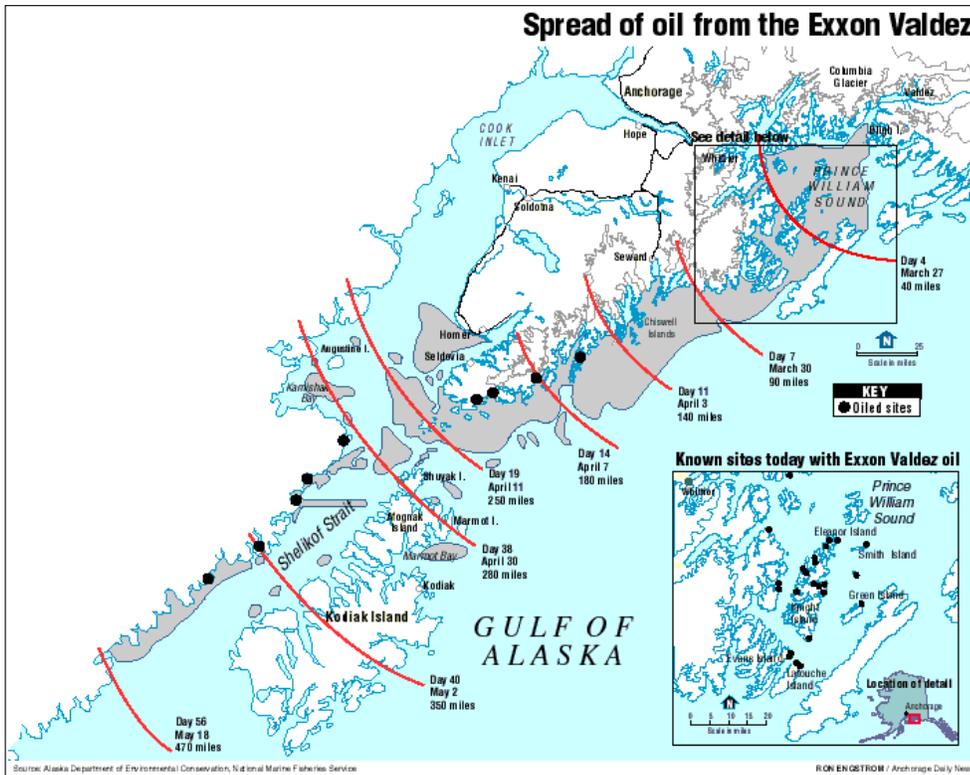


Figure 1-3 Map illustrating the direction of movement of oil from the Exxon Valdez Oil Spill from March 27 to April 18th, 1989. Alaska Daily News, Special Feature, March 21-24, 1999.

GULF WATCH ALASKA: CONSORTIUM-BASED MONITORING

The Gulf Watch Alaska and Herring Research and Monitoring programs were developed from a suite of independent studies as parallel, collaborative efforts engaged to monitor the ecosystems and resources affected by the 1989 spill for a 20-year period beginning in 2012. These programs take a collaborative, shared approach to data collection and information dissemination that allows the more than 17 different government agencies, universities, and non-governmental organizations to provide a baseline of information that can be used to develop a larger, more profound understanding of the interactions and drivers of ecosystem services within the northern GOA. This information is highly beneficial for managers and resource users, particularly in consideration of forthcoming changes in the oceans and coastal areas associated with global climate change.

The primary goal of the Gulf Watch Alaska long-term monitoring program is to provide sound scientific data on the marine ecosystem of the GOA and information products based on these data to management agencies and the public that will give us the ability to detect change. This program is a collaborative long-term monitoring program that provides data that can be used to inform modeling and process studies, but does not include direct funding of these kinds of activities. The data and data products from this program can be used to inform management decisions to accommodate changes in the environment and the impacts of these changes on resources and services that were injured by the *Exxon Valdez* oil spill (EVOS).

The program is a consortium of 15 field projects, ten of which contain data sets with over seven years of annual monitoring data and several with data sets extending prior to EVOS. The various projects within the program incorporate a suite of historical monitoring information, with some data sets dating back to the late 1970s. These long time series allow us to investigate ecological patterns in association with climatic drivers and develop hypotheses regarding potential causes of future change and facilitate management decisions. The program is designed to monitor key factors that play important roles in the ecology of the GOA marine environments and is rooted in both understanding the impact of perturbations on these resources as well as understanding other factors that are drivers of production.

Almost all of the work completed under the Gulf Watch Alaska program is possible because of the significant leveraging of funding and collaboration among the scientists of the fifteen entities involved in the program. A wider array of information and tools are also afforded through these partnerships, including advanced data housing and management services (AOOS), complete and large-scale nearshore ecological surveys under the National Park Service Southwestern Alaska inventory program (SWAN) and the University of Alaska Fairbanks(UAF)/Kasitsna Bay Laboratory (KBL)/National Estuarine Research Reserve System (NERRS) partnerships, and a wider outreach capacity through the agency partners (see Program architecture section for details). Student participation under the agency partnerships has provided for deeper investigations into marine bird abundances, forage fish sampling methods, oceanography, and sea otter diets. Finally, the recent collaboration among these various projects affords an opportunity to develop a more holistic and comprehensive view of the ecology and forcing factors in the northern GOA that we expect to continuously strengthen.

Program Architecture

The Gulf Watch Alaska program is composed of integrated program management, data services, science synthesis, conceptual modeling, historic data compilation, and outreach efforts, as well as the 15 individual ecosystem monitoring projects (Figure 1-4). Field sampling for most projects occurs each year.

EVOSTC Long-Term Monitoring Program

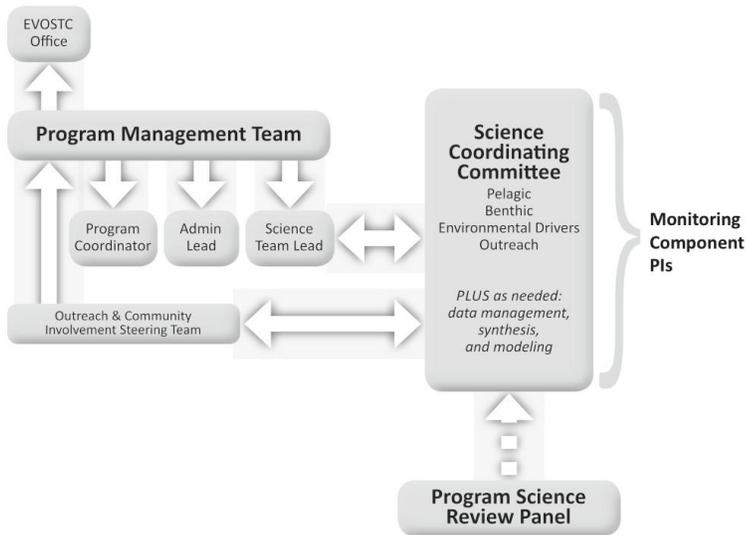


Figure 1-4. Structure of the Gulf Watch Alaska program

Integrated program management, data services, outreach, science synthesis and modeling

- Program coordination and logistics – Prince William Sound Science Center (PWSSC) and Alaska Ocean Observing System (AOOS)
- Outreach – AOOS
- Data management –AOOS/Axiom Consulting
- Historical data management and synthesis – National Center for Ecological Analysis and Synthesis (NCEAS)
- Science coordination and synthesis – NOAA Kasitsna Bay Laboratory (KBL)
- Conceptual ecological modeling– Alaska Sea Life Center (ASLC)

Environmental drivers monitoring component

- GOA mooring (GAK 1) monitoring – University of Alaska Fairbanks (UAF)
- Seward Line monitoring – UAF
- Oceanographic conditions in Prince William Sound – PWSSC
- Oceanographic monitoring in Cook Inlet – Kachemak Bay National Estuarine Research Reserve (KBNERR) and NOAA Kasitsna Bay Laboratory (KBL)
- Continuous Plankton Recorder (CPR) – Sir Alister Hardy Foundation for Ocean Science (SAHFOS)

Pelagic monitoring component

- Long-term killer whale monitoring – North Gulf Oceanic Society (NGOS)

- Humpback whale predation on herring – NOAA National Marine Fisheries Service (NMFS) Auke Bay Laboratories and University of Alaska Southeast
- Forage fish distribution and abundance – U.S. Geological Survey (USGS) Alaska Science Center
- Ability to detect trends in nearshore marine birds – U.S. National Park Service (USNPS) Southwest Alaska inventory and monitoring Network (SWAN)
- Prince William Sound marine bird surveys – U.S. Fish and Wildlife Service (USFWS)
- Winter habitat use and distribution of marine birds in Prince William Sound late fall through winter marine bird surveys – PWS – Prince William Sound Science Center (PWSSC)

Nearshore monitoring component

- Nearshore ecosystems in the GOA – USGS Alaska Science Center/ USNPS Southwest Alaska Network, Coastal Resources Associates, NOAA National Marine Fisheries Service (NMFS) Auke Bay Laboratories
- Ecological Communities in Kachemak Bay – UAF

Lingering oil component

- EVOS oil exposure of harlequin ducks and sea otters – USGS Alaska Science Center
- Oil level and weathering tracking – NOAA/NMFS Auke Bay Laboratories

Data Management and Outreach

The data management and outreach project team leads work closely to provide an integrated framework for assimilation and distribution of the information collected under the Gulf Watch Alaska program. Since the beginning of the program, data management team investigators have developed and continue to update an internal Research Workspace for management and sharing of information among study teams in addition to providing program researchers with a data portal to make information public. The GOA data portal provides resource managers and scientists outside the program access to both Gulf Watch Alaska-produced and GOA-relevant ecosystem data to improve management decisions and accelerate information synthesis.

The GWA website (www.gulfwatchalaska.org) continues to be the program's major outreach tool and is updated regularly with new project work and data. Outreach team members participate in workshops and meetings to identify best practices and lessons learned for community based monitoring (CBM) type activities in Alaska. Other outreach activities include the program sponsored Discovery Labs at the Kachemak Bay National Estuarine Research Reserve, publication of the Delta Sound Connections articles, radio segments, and seminars given by program scientists in various communities in the GOA. Upcoming activities include distance learning curricula, youth video projects, and displays.

Historic Data Compilation, Publication, and Synthesis

Data has been collected through numerous individual-directed studies and under a variety of multi-system investigations under the EVOSTC funded programs over the past 25 years. The National Center for Ecological Analysis and Synthesis (NCEAS) is working to compile and publish historic data sets from EVOSTC funded studies and provide a focused synthesis of information from select study topics developed by two working groups composed of regional scientists with focused expertise.

To date, NCEAS has been able to compile and document 27% of 419 historical data sets from past EVOSTC or relevant projects and develop and deploy the DataONE Gulf of Alaska Member node (<https://GOA.nceas.ucsb.edu>) for these historic data. In preparation for the working groups, NCEAS has provided data integration and synthesis of multiple large-scale data sets including ADCP data, sea bird data, and other spatially extensive data sets. Derived data have also been integrated into the GOA data portal. Lastly, two synthesis working groups were selected and started meeting in Fall 2014. These working groups are:

- Kristin Marshall, Anne Beaudreau, Richard Brenner, Mary Hunsicker, Eric Ward, and A. Ole Shelton. *Applying portfolio effects to the Gulf of Alaska ecosystem: did multi-scale diversity buffer against the Exxon Valdez oil spill?*
- Thomas Okey, Terrie Klinger, and James J. Ruzicka. *Understanding changes in the Coastal Gulf of Alaska Ecosystem: Analysis of Past Dynamics to Improve Prediction of Future Response to Natural and Anthropogenic Change.*

Conceptual Models: Advancing Understanding of northern Gulf of Alaska Ecosystems

Conceptual ecological models are considered a key element of environmental and biological monitoring programs, and are often used to provide a qualitative representation of the structure and dynamic properties of the ecosystem under study (Figure 1-2). The modeling process offers tools for developing, synthesizing, updating, and communicating current understanding about ecological systems. Modeling exercises are also useful for representing advances in knowledge, by updating and refining existing models with new information. Thus, conceptual ecological modeling serves multiple purposes in our program:

- Define scope and provide a scientific framework by describing current understanding of system structure, processes, and function, including key system components and their interactions.
- Provide a method to integrate current knowledge of the system using a variety of data sources, such as multiple long-term studies focusing on different species or components of the system.
- Provide critical tools to address uncertainties or incomplete understanding of ecosystem function, and help direct research priorities.
- Provide the basis for development of causal hypotheses among environmental or anthropogenic stressors, ecological effects, and link research to management actions.

Previous GOA conceptual modeling efforts have focused on describing overall structure and function of the Gulf ecosystem or natural and anthropogenic drivers in a risk assessment context (Mundy 2005, Harwell et al. 2010). The Gulf Watch Alaska program has developed and applied new modeling techniques to support program synthesis and communication goals.

ADDRESSING MANAGEMENT NEEDS AND RESEARCH QUESTIONS

The Gulf Watch Alaska program was developed to provide an integrated approach to monitoring ecosystems and ecosystem services injured and recovering from the Exxon Valdez oil spill. The program has afforded connections and partnerships from the historically independent and disjointed studies occurring in the region. Though only in its infancy, the integrated approach of the program has already made great progress in developing partnerships that leverage resources, consolidating long-term data sets to provide an integrated baseline of information, developing online resources for data publication, and most importantly, providing a framework for integrated ecosystem thinking. One tool used to promote cross-program science integration were the example research questions posed in our initial proposal

(McCammon et al. 2011) as issues relevant to management of spill affected resources. The questions were not intended to be comprehensive, but to illustrate specific examples of how integrated efforts between scientific disciplines in the Gulf Watch Alaska and the Herring Research and Monitoring programs could advance ecosystem understanding. We expect that these questions are only a small subset of hypotheses that will be addressed with monitoring program data. New results from our ongoing monitoring efforts are enabling us to enhance our knowledge of the state and function of the northern Gulf of Alaska. We also use those results to evaluate how monitoring data from the Gulf Watch Alaska program can be used to answer our integrated ecosystem questions, as well as to better refine the questions themselves. Detailed discussions of results are provided in Chapters 2-5, but we summarize our current approach to the initial cross-program research questions here.

Cross Disciplinary Research Questions

- 1) Are changes in oceanographic conditions in the outer GOA shelf mirrored in the nearshore marine environment and population trends of injured, recovering and recovered resources?

The oceanographic sampling design of the Environmental Drivers component includes sustaining long time-series measurements on the shelf at GAK1 and Seward, making routine shipboard measurements in PWS and lower Cook Inlet to assess estuary conditions and estuary-shelf linkages, and leveraging shore station measurements in Kachemak Bay and at NOAA water level stations. As discussed in detail in Chapter 2, there is significant coherence in shelf and nearshore oceanographic conditions for time periods greater than one to three months, but not at shorter time periods. Therefore we expect that the Gulf Watch Alaska monitoring data will provide information to address environmental forcing questions for nearshore species at longer time periods (seasonal, annual, interannual). However, more frequent environmental observations may be required at additional nearshore sites, to assess forcing of biological processes at shorter time scales. The scientists of the Environmental Drivers and Nearshore components are working together to determine these requirements.

- 2) Are population trends of nearshore and pelagic injured, recovering and recovered species responding similarly to changes in ocean conditions?

Ocean conditions are warming (with periods of cooler temperatures in the GOA), becoming less saline at the surface and becoming more stratified (see Environmental Drivers component discussion in Chapter 2). Forage fish populations experienced significant fluctuations due to multiple perturbations over the last several decades, with cause and effect not yet fully determined. Nearshore and pelagic marine birds have also experienced significant population fluctuations, with a variable response among different species. Specifically, some piscivorous pelagic species have dramatically declined, while nearshore benthic omnivores remained unchanged. The three ecotypes of killer whales all have different trajectories due to their different positions in the ecosystem and impacts of the oil spill. An increase in humpback whales has possibly depressed forage fish populations. The long-term monitoring of these species and marine conditions in the Gulf Watch Alaska program is providing the critical data for answering this question on ecosystem response to environmental changes.

- 3) Is herring and forage fish overwintering success tied to spring and summer productivity and seasonal or year-to-year differences in the zooplankton community?

Through discussions with Herring Research and Monitoring program scientists we determined that, as stated, this question could not be addressed with current data collection. However, the question can be refined to the following:

Are herring and forage fish fall body condition and size tied to spring and summer productivity and seasonal or year-to-year differences in the zooplankton community?

Data currently collected under the Herring Research and Monitoring program in conjunction with data collected under the Environmental Drivers component (plankton information collected from Batten and Campbell projects) are being used to examine this question in more detail. Some discussion and preliminary correlative associations between herring first year growth and annual plankton abundances (from CPR data) are included in Pegau et al. (in review), the complementary synthesis report submitted to the EVOSTC for the Herring Research and Monitoring program.

- 4) Is herring and forage fish overwinter success associated with winter conditions on the shelf or in PWS?

As with the previous question, we have jointly determined with the herring scientists that, as stated, this question could not be addressed with current data collection. Refining the question, we could address the following:

Are herring and forage fish fall body condition and size associated with winter conditions on the shelf or in PWS?

Data currently collected under the Herring Research and Monitoring program in conjunction with plankton and water temperature data collected under the Environmental Drivers component is being used to examine this question in more detail.

- 5) Are variations in seabird abundance and distribution associated with zooplankton stocks and/or oceanographic conditions?

Currently, we are not collecting data with the appropriate spatial and temporal resolution to address this question comprehensively within the Gulf Watch Alaska program. However, we are finding that seabirds, killer whales, humpback whales, and forage fish concentrate seasonally in some locations (e.g. Montague Strait in PWS). Environmental Drivers component data may help us identify the mechanisms creating these biological hot spots or, conversely, the predator-prey aggregations may identify areas where we need to collect additional environmental data. We are refining our research question as follows:

Are recurring spatial patterns in predator foraging aggregations (hot spots) associated with particular oceanographic conditions?

To answer this cross-cutting question we will assess locations and causes of multi-species aggregations. We expect that “hot spot” analyses will also allow us to learn about drivers of marine productivity in the system and better understand factors that are enhancing (and limiting) recovery of injured resources.

- 6) What are predation rates of humpback whales and seabirds on PWS herring and other forage fish populations? (to be applied in herring population modeling efforts).

The humpback whale and seabird monitoring data collected in the Gulf Watch Alaska program are being used to estimate predation rates on herring, and results continue to show that these predators exert top-down forcing on herring populations. However, the ecosystem response is complex, as an increase in alternative prey such as capelin or euphausiids may reduce impacts on herring stocks. For example, there is evidence of a cyclic pattern of abundance for some forage fish species (ie, sand lance.), which could lead to a cyclic pattern in seabird predation on herring. From current findings, we have added the following additional cross-cutting research question:

Will humpback whale and seabird predation rates on herring change as prey fields change in response to environmental drivers?

We also developed the following four questions addressing spatial and temporal variability in environmental conditions and primary and secondary plankton production in the northern GOA, PWS and Cook Inlet:

- 7) How do oceanographic patterns compare (and co-vary) between different locations in PWS, GOA shelf, and lower Cook Inlet?
- 8) What are the spatial patterns and timing of ocean stratification that lead to spring and autumn phytoplankton blooms?
- 9) How are the timing, intensity and duration of stratification changing, and what are the consequences?
- 10) How do zooplankton community assemblages and abundances vary spatially, from year to year, with the timing of the spring phytoplankton bloom, and with water properties (temperature, salinity, nutrients)?

Results to date from oceanography and plankton monitoring have confirmed the value of long-term oceanographic time series for assessing decadal-scale environmental changes and we are starting to see some patterns emerge in comparisons across the region. The preliminary analyses are described in detail in Chapter 2 and summarized in the Executive Summary. While coherent patterns in temperature and salinity time series are observed at seasonal, interannual and decadal time scales within the northern GOA, there is considerable regional variability in environmental conditions at shorter time scales. This variability will also drive spatial differences in species that respond at these time scales and raises questions on the space and time scales at which environmental conditions should be monitored to assess linkages to lower trophic levels and subsequent impacts at higher trophic levels. We expect that these questions will remain relevant to understanding how environmental changes affect production and bottom-up forcing of the GOA ecosystems. For further details, please see Chapter 2 Environmental Drivers: Regional Variability in Oceanographic Patterns Across the Gulf of Alaska.

- 11) What are the population trends of key pelagic species groups (killer whales, seabirds, humpback whales, and forage fish) in PWS?
- 12) How can forage fish population trends in PWS be effectively monitored?

The Gulf Watch Alaska program scientists continue to conduct the critical monitoring needed to assess population trends of killer whales, seabirds and humpback whales and are conducting a pilot project in PWS to improve forage fish monitoring methods. The key findings to date are summarized in the

Executive Summary, with details provided in Chapter 3 Variability within Pelagic Ecosystems of Prince William Sound. Tracking population trends provides key information to assess post-EVOS species response and, as discussed for earlier research questions, we are also now investigating predator-prey hot-spots as a way of better understanding ecosystem relationships. Assessment of population trends in seabirds also requires collaboration with and data from other agencies (ADFG, USFWS) and organizations. A new combined shipboard-aerial survey approach is being tested to improve forage fish monitoring, but comprehensive determination of forage fish population trends is expected to be very resource intensive. Please see Chapter 3, Forage Fish Populations in Prince William Sound: Designing Efficient Monitoring Techniques to Detect Change for additional information on the forage fish project.

- 13) Are there significant inter-annual changes in the nearshore communities and are they synchronous across the GOA?

Nearshore component data are being used to investigate temporal and spatial changes in nearshore communities. For one example, the influence of the local environment (e.g. presence of glaciers, exposure) was found to be a minor driver of community structure at rocky intertidal sites, with stronger effects from regional influences and tidal elevation (Konar et al., this report). In the second example, over the period from 2007 to 2013, we have observed a significant reduction in mussel abundance across the Gulf of Alaska (Monson et al., this report). That decline in mussels correlates with changes in sea otter and black oystercatcher diets. Further, the geographic scope of synchronous mussel abundance changes suggests they may reflect changes in the pelagic marine environment and that is a discussion among the Nearshore and Environmental Drivers component scientists. Please see Chapter 4 Variability within Nearshore Ecosystems of the Gulf of Alaska for further details.

- 14) Have injured resources in the nearshore environment recovered from EVOS? If not, can we identify or rule out other, non-spill related, factors that are constraining their recovery?

The effects of the *Exxon Valdez* oil spill on some vulnerable wildlife, particularly sea otters and harlequin ducks, have been observed for more than two decades. Recent findings indicate that evidence of exposures to lingering oil in these species are no longer detectable and that their population status is consistent with recovery as defined by the EVOSTC. Lingering oil is known to remain in the environment and sites will be surveyed under the Gulf Watch Alaska program in 2015 to assess presence and weathering. Herring populations are still below pre-EVOS levels and we continue our collaborations with the Herring Research and Monitoring program to assess top-down and bottom-up ecosystem forcing. As described in earlier questions, Gulf Watch Alaska monitoring data is being used to measure and understand drivers for population changes in multiple species. For further details on lingering oil studies, please see Chapter 5 Lingering Oil Monitoring.

MOVING FORWARD: FUTURE VISION FOR THE GULF WATCH ALASKA PROGRAM

Moving forward, the initial synthesis results confirm the value of long term monitoring for ongoing management of EVOS-affected resources in the GOA. These long-term time series will allow for detection of population changes in injured and recovering resources in the face of variable environmental conditions. In addition, we hope to continue to build upon work currently underway to provide access to and use of the program information for resource management and research. We will continue to build integration within the Gulf Watch Alaska program, with the Herring Research and Monitoring program, and with other research programs in the Gulf of Alaska. We also recognize the importance developing a

better understanding of the ecological processes and drivers of variability in the ecosystems of the Gulf of Alaska, to better inform coastal resource managers. Supporting student internships and post-doctoral positions is a potential mechanism to conduct additional integrated data analyses and process studies and they will also provide workforce capacity to ensure continuity in the long-term monitoring programs.

REFERENCES

- A'mar, T., K. Aydin, E. Conners, C. Conrath, M. Dalton, O. . Davis, M. Dorn, K. Echave, N. Friday, K. Green, D. Hanselman, J. Heifetz, P. Hulson, J. Ianelli, D. Jones, M. Jaenicke, S. Lowe, C. Lunsford, S. Meyer, C. McGilliard, D. Nichol, O. Ormseth, W. Palsson, C. Rodgveller, J. Rumble, K. Shotwell, L. Slater, K. Spalinger, P. Spencer, I. Spies, I. Stewart, M. Stickart, W. Sockehausen, D. Stram, T. TenBrink, C. Tribuzio, and J. Turnock. 2013. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. Pages 1–52. Anchorage, AK.
- ADMM. 1964. The Great Alaska Earthquake, March 17, 1964.
- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift.pdf. *Marine Ecology Progress Series* 189:117–123.
- Beamish, R. ., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. *Progress in Oceanography* 49(1-4):423–437.
- Dean, T. A., and J. L. Bodkin. 2006. Sampling protocol for the nearshore restoration and ecosystem monitoring (N-REM) program. Anchorage, AK.
- Di Lorenzo, E., V. Combes, J. E. Keister, P. T. Strub, A. C. Thomas, P. J. S. Franks, M. D. Ohman, J. C. Furtado, A. Bracco, S. J. Bograd, W. T. Peterson, F. B. Schwing, S. Chiba, B. Taguchi, S. Jormazabal, and C. Parada. 2013. Synthesis of Pacific Ocean Climate and Ecosystem Dynamics. *Oceanography* 26(4), 22-33.
- Durant, J., and D. Hjerermann. 2007. Climate and the match or mismatch between predator requirements and resource availability. *Climate ...* 33:271–283.
- Eslinger, D. L., R. T. Cooney, C. P. Mcroy, A. Ward, T. C. Kline, E. P. Simpson, J. Wang, and J. R. Allen. 2001. Plankton dynamics: observed and modelled responses to physical conditions in Prince William Sound, Alaska. *Fisheries Oceanography* 10:81–96.
- Gargett, A. E. 1997. The optimal stability “window”: a mechanism underlying decadal fluctuations in North Pacific salmon stocks? *Fisheries Oceanography* 6(2):109–117.
- Harwell, M. A., J. H. Gentile, K. W. Cummins, R. C. Highsmith, R. Hilborn, C. P. Mcroy, and T. Weingartner. 2010. Human and Ecological Risk Assessment : A Conceptual Model of Natural and Anthropogenic Drivers and Their Influence on the Prince William Sound , Alaska , Ecosystem. *Human and ecological risk assessment HERA (May 2013):*672–726.

- Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. *Marine Ecology Progress Series* 477:271–284.
- Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific basin climate variability and patterns of Northeast Pacific marine fish production. *Progress in Oceanography* 49(1-4):257–282.
- Ladd, C. 2007. Interannual variability of the Gulf of Alaska eddy field. *Geophysical Research Letters* 34(11):L11605.
- Mackas, D. L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. *Progress in Oceanography* 75(2):223–252.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78(6):1069–1079.
- Mueter, F. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. *Canadian Journal of ...* 463:456–463.
- Mueter, F., D. Ware, and R. Peterman. 2002. Spatial correlation patterns in coastal environmental variables and survival rates of salmon in the northeast Pacific Ocean. *Fisheries Oceanography* (October 2001):205–218.
- Mundy, P. R. 2005. *The Gulf of Alaska Biology and Oceanography*. P. R. Mundy, editor. Alaska Sea Grant College Program, University of Alaska Fairbanks.
- Omar I. Abdul-Aziz, N. J. Mantua, and K. W. Myers. 2011. Potential climate change impacts on thermal habitats of Pacific salmon (*Oncorhynchus* spp.) in the North Pacific Ocean and adjacent seas. *Canadian Journal of Fisheries & Aquatic Sciences* 68:1660–1680.
- Overland, J. E., J. Alheit, A. Bakun, J. W. Hurrell, D. L. Mackas, and A. J. Miller. 2010. Climate controls on marine ecosystems and fish populations. *Journal of Marine Systems* 79(3-4):305–315.
- Rose, G. 2005. Capelin (*Mallotus villosus*) distribution and climate: a sea “canary” for marine ecosystem change. *ICES Journal of Marine Science* 62(7):1524–1530.
- Schoch, K., G. Eckert, and T. A. Dean. 2002. Long-term monitoring in the nearshore: Designing a program to detect change and determine cause. Anchorage, AK.
- Shriver, J. 2012. Changes in Gross Total Earnings in Selected Alaska Salmon Fisheries, 1975-2011. CFEC Report 12-07-N. Juneau, ak.
- Spies, R. B., editor. 2006a. Long-term ecological changes in the northern Gulf of Alaska, 1st edition. Elsevier Science.

Spies, R. B. 2006b. Long-term ecological change in the northern Gulf of Alaska. Elsevier Science.

Springer, A. M., and G. B. Van Vliet. 2014. Climate change , pink salmon , and the nexus between bottom-up and top-down forcing in the subarctic Pacific Ocean and Bering Sea. PNAS:1–9.

Stachura, M. M., N. J. Mantua, and M. D. Scheuerell. 2014. Oceanographic influences on patterns in North Pacific salmon abundance. Canadian Journal of Fisheries & Aquatic Sciences 71(October 2014):226–235.

Chapter 2 ENVIRONMENTAL DRIVERS: REGIONAL VARIABILITY IN OCEANOGRAPHIC PATTERNS ACROSS THE GULF OF ALASKA.

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Introduction to Monitoring of Environmental Drivers

In the 25 years following the *Exxon Valdez* oil spill (EVOS), numerous studies and efforts have been conducted to understand the impacts of the spill on the region and restore injured resources through work funded by the *Exxon Valdez* Oil Spill Trustee Council (Mundy 2005, Spies 2006b, Harwell et al. 2010). As time has progressed, chronic effects directly related to the spill have become more difficult to ascertain due to attenuation of the oil within the environment, changing climate, natural variability, and anthropogenic changes (e.g. fishing and other industrial pressures, pollution with added vessel traffic from maritime commerce and tourism). Long-term observations are fundamental requirements to detect ecological changes due to an oil spill or any other unknown drivers. As recognized in the 1994 EVOS Restoration Plan, effective restoration requires an adaptive management cycle that updates restoration activities as new information and understanding is acquired. The projects within the environmental drivers component of the program monitor physical conditions and plankton within the marine environment. These are key factors driving ecological processes and food web interactions within our oceans and important conditions to consider when evaluating recovery of spill-affected resources, the impact of climate change on marine ecosystems, and estimating weathering of remaining oil.

We live in a constantly changing world, influenced by a combination of stochastic events, natural cycles, longer-term oscillations, and the accelerating impact of human activities. Once thought to house relatively stable ecosystems, the oceans are now known to fluctuate between multiple states or “regimes” apparently coupled to major climatic shifts such as the Pacific Decadal Oscillation (PDO). This knowledge was derived initially from long-term and global views of physical changes in the ocean and atmosphere, but most importantly from long-term biological observations that demonstrate the impact of “regime shifts” (Francis and Hare 1994, Mantua et al. 1997). Such regime shifts may be common (Hare and Mantua 2000), and we are beginning to appreciate the mechanisms by which these physical changes impact ecosystems (McGowan et al. 1998, Beaugrand 2004).

Biological time-series such as the North Atlantic Continuous Plankton Record (CPR; Beaugrand 2004), the North Pacific California Cooperative Oceanic Fisheries Investigations (CalCOFI; McGowan et al. 1998), Line P (Mackas et al. 2004), and the younger CPR program (Batten and Freeland 2007) in the subarctic Pacific are proving invaluable at documenting regime shift-related changes in lower trophic level species distributions (Beaugrand and Reid 2003, Lavaniegos and Ohman 2007) and timing of life

histories (Mackas et al. 1998). In the Gulf of Alaska, the 1976 regime shift resulted in a change from a crab and shrimp-dominated fishery to one dominated by pollock, salmon and halibut (Anderson and Piatt 1999). Understanding how complex pelagic ecosystems work, and how they might be affected by climate change, was the fundamental goal of the Global Ecosystem Dynamics (GLOBEC) program that occupied the Seward Line in the northern Gulf of Alaska from 1997 to 2004 (Weingartner et al. 2002). One of the core hypotheses of that program revolved around the observed out-of-phase covariance of the zooplankton production (Brodeur et al. 1996), and of the fish populations such as salmon that feed on them (Hare et al. 1999). The existence of a second regime shift during the past decade, to a new bimodal state dominated by the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008), still remains debated.

To understand the variability in ecology and physical forces within the Gulf of Alaska (GOA), we must appreciate both the challenges imposed by its sheer size, as well as the oceanographic complexity of this ecosystem. The physical environment of the GOA shelf and adjacent bays are a consequence of its high-latitude setting, seasonally-varying atmospheric pressure systems, and geomorphological features that include an extensive range of coastal mountains populated by numerous glaciers. In aggregate, these features establish the circulation and water property (temperature, salinity, nutrients) fields that subsequently structure the marine ecosystem and affect rates of marine production. Viewed from a broad perspective, the shelf circulation involves a continuous counterclockwise flow over the shelf and continental slope that transports waters around the GOA and ultimately into the Bering Sea and/or back into the North Pacific Ocean. The Alaska Coastal Current (ACC) is the most prominent feature of the Gulf of Alaska's shelf circulation (Figure 2-1). It is a narrow (approximately 40 km), swift ($10 - 40 \text{ cm s}^{-1}$), year-round flow maintained by winds and coastal freshwater discharge. These are spatially- and temporally-integrated forcings governed by weather systems associated with the Aleutian Low and their interaction with the coastal mountains. This influence is reflected in the properties of the shelf and its adjacent bays including ocean heat budgets, stratification, and density fields.

The ACC originates on the British Columbian shelf and exits the Gulf for the Bering Sea through Unimak Pass. Substantial portions of the ACC circulate through Prince William Sound and feed lower Cook Inlet before flowing southwestward through Shelikof Strait. The ACC also controls water exchanges between the numerous fjords and bays indenting the GOA coastline. These exchanges are important in modifying the properties of both the shelf and the embayments involved in the exchange. Although the ACC may be thought of as the common thread linking various regions of the coastal GOA, it is important to recognize that each region is subject to local forcing, which may cause considerable spatial variability in the physical structure of the environment. This spatial variability gives rise to the enormous diversity in marine habitats distributed throughout the coastal GOA.

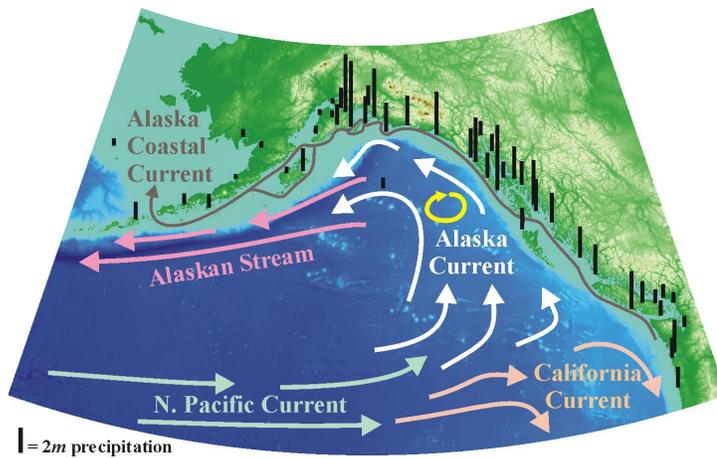


Figure 2-1. Schematic of the circulation of the Northeast Pacific and Gulf of Alaska (from Weingartner et al, 2002). The vertical bars are the mean annual precipitation amounts at selected National Weather Service coastal sites and in the interior of the Gulf of Alaska.

Oceanographic variations in the environment are assessed in the Gulf Watch Alaska program within four general regions (Figure 2-2) within the northern Gulf of Alaska: the Gulf of Alaska shelf both along the Seward Line and with the CPR program, the ACC via hydrographic station GAK 1, Prince William Sound (PWS), and lower Cook Inlet/Kachemak Bay. Each of these programs (Figure 2-3) provides information at different spatial or temporal scales, which in aggregate provide a robust assessment of the northern GOA. Several of these monitoring efforts, the Seward Line, CPR, and Kachemak Bay programs, are highly leveraged, with upwards of 75% of the funding provided by non-EVOSTC sources. In addition, each of these programs builds on an existing time series typically of more than a decade in duration.

Cook Inlet monitoring has focused on oceanography and plankton sampling in the lower part of the Inlet, including Kachemak Bay, in order to assess seasonal and inter-annual variability with detailed cross-inlet and cross-bay spatial resolution. Information from inlet-bay and shelf-estuary exchange (in collaboration with Weingartner, Hopcroft and Batten projects on the GOA shelf) and regional comparisons with Prince William Sound conditions (in collaboration with Campbell project) provide environmental data for the nearshore component monitoring efforts of Gulf Watch Alaska (Konar and Iken project) and for harmful algal bloom and ocean acidification research (separate NOAA and ADFG studies). Both lower Cook Inlet and Kachemak Bay receive waters derived from the GOA shelf and both are subject to locally modifying influences, including short period transport and mixing variability due to large tidal excursions (~9 meter maximum vertical range), runoff from rain, snowpack, and glacier melt, and topographically-steered winds.

Prince William Sound is a semi-enclosed embayment having features common to both inland seas and fjord systems. In addition, the Sound hosts a multitude of smaller bays and fjords each subject to a diversity of tidal influences, glacial and non-glacial watersheds, and bathymetric variations that include bay entrances with and without sills. These variations provide a variety of marine habitats but complicate describing variability throughout the Sound in any succinct manner. Given the available data distribution

we have instead followed Musgrave et al. (2013) in segregating the Sound into a number of regions that capture common geomorphological and/or dynamical features.



Figure 2-2. Schematic circulation of the northwest Gulf of Alaska, showing the northwestern Gulf of Alaska, which encompasses the four principal Gulf Watch Alaska sampling regions: Prince William Sound, the Seward Line, GAK 1, and Lower Cook Inlet, including Kachemak Bay adjacent to Homer.

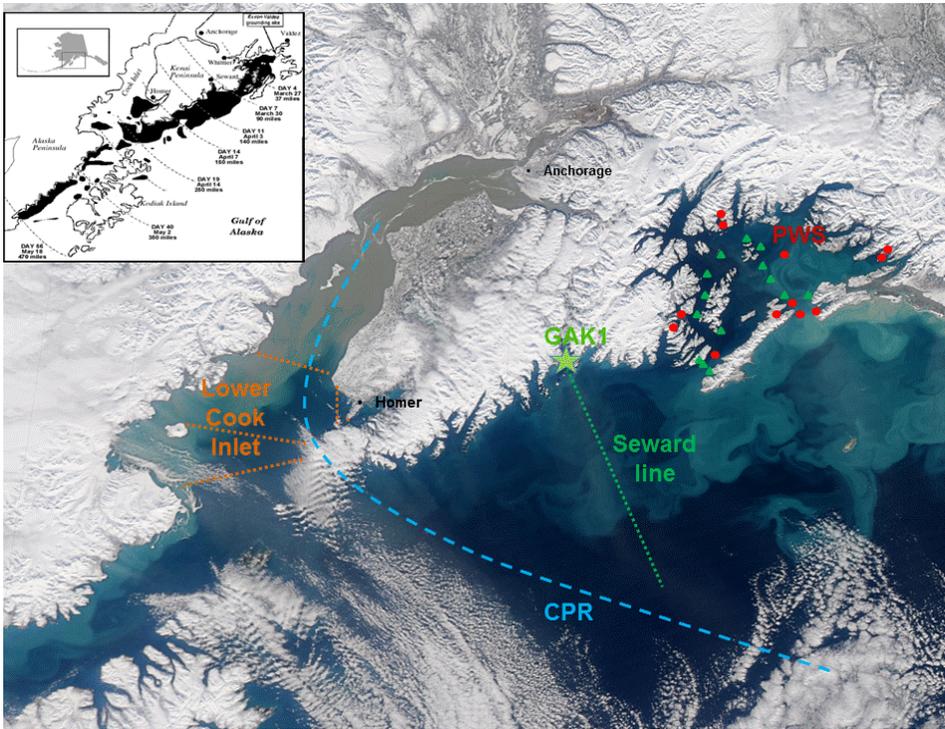


Figure 2-3. Map showing current locations of Gulf Watch Alaska oceanographic sampling in: Lower Cook Inlet (orange); Seward line and Gulf of Alaska (GAK 1, green); Continuous Plankton Recorder (CPR, blue) and Prince William Sound (PWS, red).

Although there are tremendous regional (and sub-regional) differences present throughout the Gulf Watch Alaska study area, a number of common features have emerged from the various data sets obtained over the course of the program and from the historical data sets within this area. These features are summarized in the following discussion.

Long-term warming trend

Royer and Grosch (2006) showed a multi-decadal trend in warming on the GOA shelf up through the early 2000s based on the historical record at GAK 1. The additional decade of data collected at GAK 1 since then allows a re-assessment of their results. We find that this long-term warming trend over the Gulf of Alaska has continued and is evident in both the 43-year time series at GAK 1 and the shorter, and more gapped record from waters offshore of Prince William Sound and within the central portion of the Sound. The warming trend is occurring throughout the water column and amounts to approximately $0.25\text{ }^{\circ}\text{C decade}^{-1}$ at the surface and over the upper 100 m of the water column and approximately $0.15\text{ }^{\circ}\text{C decade}^{-1}$ over the 100 – 200 m depth range. These trends are slightly lower than those reported by Royer and Grosch (2006), which we ascribe to several colder years (particularly from 2007 – 2009) that have occurred in the past decade. In fact several of these winters were amongst the coldest observed since the early 1970s (Janout et al. 2010, Janout et al. 2013). [The results described here also only capture the ADD Pacific warm blob comment](#)

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Salinity trends

Salinity trends have shown opposite directions over the water column. Surface salinities and salinities over the upper 100 m of the water column have decreased by approximately 0.6 and 0.2, respectively since 1970, while the average salinity between 100 and 200 m depths have increased by approximately 0.1. The surface salinity trend is consistent with an increasing trend in discharge over the same time period based on the Royer (1980) approach to estimating GOA runoff. More recent estimates (Hill et al. in review) also indicate an increasing trend in discharge. Part of this discharge increase is associated with an increase in precipitation and part is due to net ablation of the glacial fields surrounding the coastal GOA (Neal et al. 2010). The freshening of the surface salinity observed here is also consistent with broader trends observed over the northern North Pacific Ocean (Durack and Wijffels 2010) and reflects the acceleration of the global hydrologic cycle in response to a warming climate.

The observed salinity increase in deeper waters (amounting to approximately 0.1) is substantial, but the cause for the increase is not clear. Several possible mechanisms may be responsible. First, the increase in stratification may simply result in less vertical mixing so that the deeper waters are not freshened as efficiently as in the past. This effect is aggravated by the observation that shelf wind speeds are decreasing, since the wind is the primary source of energy for mechanical mixing of the upper ocean. While climate projections indicate that there will be long-term increase in coastal discharge, it is not clear if there will be a sustained decrease in wind speed. Alternatively (or in conjunction with changes in wind mixing and discharge), the deep salinity increase could reflect either a greater influx of high-salinity slope waters onto the GOA shelf. From a theoretical perspective a more efficient transfer of deep slope waters onto the shelf would occur if the along-shelf wind stress is decreasing (Chapman 2000). The infusion of saline slope water occurs annually on the GOA shelf with the annual relaxation in downwelling winds (Weingartner et al. 2005), in agreement with this theory. However, we have not found any significant change in the alongshore wind stress over the GOA shelf since 1970, so this mechanism does not appear to be a cause of the deep salinity increase. Third, increased runoff might induce an entrainment-like flow, which induces onshore deep water renewal. This mechanism of enhanced estuarine circulation may be especially relevant to portions of Prince William Sound and Cook Inlet, but less likely over the shelf. Fourth, the salinity of the deeper waters over the continental slope may be increasing slowly. To address this possibility would require examining the time series of subsurface salinities generated by Gulf of Alaska Project ARGO that are now routinely profiling the GOA basin.

Stratification increase and implications for primary/secondary production

The trends of upper layer freshening and lower layer salinization imply that the stratification over the inner shelf and PWS is increasing, with a trend yet to be established for Cook Inlet. Such changes have a number of potentially significant biological implications. For example, there is an optimal level of stratification (or water column stability) for phytoplankton production. If the stratification is too weak then phytoplankton are easily washed out of the euphotic zone, become light-limited, and production decreases. If the stratification is too strong, then vertical mixing and nutrient replenishment of the euphotic zone by mixing from deeper depths is inhibited. There are however, two possible scenarios associated with these salinity trends. The runoff is rich in the essential micronutrient iron, but low in the macronutrient nitrate, which can be limiting, at least seasonally, on the GOA shelf, PWS, and lower Cook Inlet (Childers et al. 2005, Strom et al. 2007). Hence, while we expect iron to be relatively abundant in these regions, the nitrate supply may be decreasing. Diminishing nitrate concentrations in the euphotic zone may gradually cause a shift in the phytoplankton community structure toward smaller species, with

subsequent effects on zooplankton community structure, abundance, and biomass (e.g. Coyle et al. 2012). Alternatively, the increase in salinity at depth implies an increase in nutrients (particularly nitrate, Childers et al. 2005) that if mixed into iron-rich surface waters could enhance production by larger-sized phytoplankton. In either case, these changes are expected to affect the structure, abundance, and biomass of the shelf zooplankton community. How these competing processes and the increase in stratification will affect primary and secondary production in the short-term remains speculative. For example, production at both levels may increase over the short-term if the regional stratification trend is moving to more optimally stable conditions. However, in the long-term an increase in stratification will result in less optimally stable conditions (at least for some species) and so alter productivity patterns throughout the northern GOA.

Changes in stratification may also influence the seasonal distribution of ocean temperatures. In summer, stronger stratification traps solar radiation in over a shallower depth range and inhibits entrainment of cooler subsurface waters. In winter, stronger stratification also inhibits vertical mixing, but in this case, warmer water has moved into the surface layers so that atmospheric cooling is confined to a relatively shallow surface layer (Janout et al. 2012).

Relationship with basin-scale climate indices

We have also examined the correlation between broad-scale climate indices and temperature and salinity variations in the Gulf of Alaska. For example, an analysis was done using the GAK 1 time series (the longest dataset available) and the following climate indices: the Pacific Decadal Oscillation (PDO), the Southern Oscillation Index (SOI, characterizes the state of the equatorial Pacific Ocean in terms of the El Niño-La Niña state), and the North Pacific Gyre Oscillation (NPGO). These indices capture penta-decadal and decadal scale climate patterns that reflect re-organization of the ocean and atmosphere of the North Pacific Ocean (for the SOI and PDO) and the northeast Pacific (for the NPGO). Independently computed linear correlations between these indices and the GAK 1 data yield the following results. We found that the PDO index explains approximately 38% of the temperature variance, but less than 15% of the salinity and discharge variance. In all cases, the maximum correlation occurred with the PDO index leading the GAK 1 data by from two to three months. The SOI index explains approximately 20% of the temperature variance and leads the temperature signal by from eight to nine months. This index is maximally correlated with salinity when leading by six to seven months, but it explains less than 10% of the salinity variability. This analysis did not demonstrate a linkage to the NPGO.

While these broad-scale trends have been emphasized in this summary, there is considerable spatial and temporal variability in all of the time series examined. For example, initial results show that at short periods (less than one month), lower Cook Inlet and GAK 1 temperature and salinity variability are poorly correlated (See Figure 2-18 in Cook Inlet summary of this chapter), and we expect similar findings for Prince William Sound. This is not unexpected given the diversity of dynamic influences operating in each sub-region. Since some of this short period variability can occur at critical life stages for marine organisms, spatial and temporal variations in production are expected to be quite large. The strength of a sustained monitoring program is in quantifying this variability, its causes, and discerning trends that may have important economic and management implications.

Key Findings

The environmental drivers component has focused on describing several key properties that appear common to the Gulf Watch Alaska area. In this section we summarize these findings, provide the mechanisms responsible for these (where known) and conclude with the potential ecological implications.

- 0.20 °C decade⁻¹ temperature increase at surface and over upper 100 m
- 0.15 °C decade⁻¹ temperature increase at between 100 - 200 m
- 0.15 decade⁻¹ salinity decrease at surface
- 0.05 decade⁻¹ salinity decrease over upper 100 m
- 0.025 decade⁻¹ salinity increase over 100 - 200 m
- There is strong evidence of bottom-up forcing in that phytoplankton and zooplankton abundance, timing and composition are each related to the physical environment. Zooplankton density is significantly related to phytoplankton density on an annual basis.
- There is strong interannual variability in physical variables and the plankton, even between adjacent years. Interannual variability is much greater than the variations associated with trends.
- The developmental timing of copepods is strongly driven by temperature and that will influence when their peak abundances occur.

These findings imply a number of additional physical and/or biogeochemical changes for the northern Gulf of Alaska. Stratification is increasing as a consequence of the salinity trends and the onset of springtime stratification that triggers the spring bloom may become earlier. The nutrient regime should also be changing with increasing discharge. Within the euphotic zone, the iron supply is increasing but the nitrate supply is decreasing. In contrast, nitrate concentrations below the euphotic zone are increasing, although it is not clear if this increase can ever be made available to the primary producers given the changes in stratification. The freshening of the upper ocean implies a decrease in total alkalinity or the buffering capacity at the surface due to increasing coastal discharge, while the increasing sub-surface salinities are accompanied by lower pH waters that may be undersaturated with respect to aragonite

In aggregate these changes will affect primary and secondary production. If these trends continue, we expect a decrease in ocean productivity, although we cannot ascribe a time scale to the decline. If stratification is occurring earlier in spring then the spring bloom may be influenced by light availability and phytoplankton community structure may change. Changes in the seasonal phasing of the spring bloom or in metabolic rates due to a warming environment could lead to a timing mismatch between prey and predators that extends throughout the trophic system. The phytoplankton and zooplankton community structure are expected to change with the nutrient supply. Finally, there are a number of zooplankton species, such as pteropods, that are critical to the ecosystem as well as prey to salmon. These organisms appear particularly susceptible to the negative effects of ocean acidification.

Recommendations

Both short- and long-term perspectives on this marine ecosystem would not be possible without sustained and systematic observational efforts. The complementary sampling efforts of the environmental drivers

program have enabled us to understand broad-scale (PWS, northern Gulf of Alaska shelf, and Lower Cook Inlet) patterns in the physical environment and the plankton communities. Surface physical variables are coherent at approximately monthly time-scales, but coherence falls off rapidly at shorter periods.

1. PAR sensors should be installed over the Gulf Watch Alaska sampling region including offshore (e.g., at Middleton Island) and inshore, the profiling mooring maintained by Campbell in Prince William Sound, Kodiak, and, Chiswell Islands to allow ease of logistics in servicing.
2. Sunlight is a critical parameter affecting primary production and the Gulf of Alaska is frequently light-limited due to cloud cover. Meteorological forecast and re-analysis models poorly estimate photosynthetically available radiation (PAR). Cross spatial scale synthesis should be conducted by comparing temperature records collected by the nearshore component using an analysis similar to the one we conducted between Seldovia and the GAK 1 mooring. Our understanding of the northern GOA ecosystem would be improved through a better understanding of the connection between shelf and coastal changes with changes in water column properties and stratification in the basin offshore of the shelf using the ARGO array.
3. Spatial and temporal variation is high in the sampling design capable of making inferences across the GOA. Therefore we recommend establishing accessible temporally-intensive monitoring sites at logistically tractable locations (e.g. coastal labs) to improve the ability to interpret and apply nearshore data.
4. Event-scale processes, such as the introduction of nutrients into the surface waters, are important to stimulating surface production and are not captured by the present sampling design (except at the profiling mooring). We require continuous measurements in order to capture these important intermittent events and their variability.
5. Consideration should be given to applying and validating coastal water algorithms appropriate for the Gulf Watch Alaska region. Satellite-derived estimates of surface chlorophyll concentrations in the Gulf of Alaska are inherently biased and potentially misleading because the detection algorithm does not adequately account for suspended sediments and color-dissolved organic matter.

The remainder of this chapter summarizes selected results from the various Environmental Drivers projects. For the synthesis we have chosen to focus on longer-period changes of ecological relevance that we presume are highly relevant to other Gulf Watch Alaska programs and the Herring Research and Monitoring Program. In order of presentation, the following sections are:

1. Long-term monitoring of oceanographic conditions in the Alaska Coastal Current from hydrographic station GAK 1;
2. The Seward Line: 17 years of pattern and variability in the coastal Gulf of Alaska;
3. Linking variability in oceanographic patterns between nearshore and shelf waters across the Gulf of Alaska;
4. Interannual variability in lower trophic levels on the Alaskan shelf
5. Hydrographic trends in Prince William Sound, Alaska, 1960 – 2013.

References

- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift.pdf. *Marine Ecology Progress Series* 189:117–123.
- Batten, S.D. and Freeland, H.J. 2007. Plankton populations at the bifurcation of the North Pacific Current. *Fisheries Oceanography*, 16, 536-646.
- Beaugrand, G., 2004. The North Sea regime shift: evidence, causes, mechanisms and consequences. *Prog Oceanogr* 60:245-262
- Beaugrand, G., Reid, P.C., 2003. Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Global Change Biol.* 9, 801-817.
- Brodeur, R.D., Frost, B.W., Hare, S.R., Francis, R.C., Ingraham, W.J., Jr., 1996. Interannual variations in zooplankton biomass in the Gulf of Alaska, and covariation with the California Current zooplankton biomass. *California Cooperative Oceanic Fisheries Investigations Rep.* 37, 80-99.
- Chapman, D. C. 2000. Boundary layer control of a buoyant coast currents and the establishment of a shelfbreak front. *J. Phys. Oceanogr.*, 30: 2941–2955
- Childers, A. R., T. E. Whitedge, and D. A. Stockwell. 2005. Seasonal and interannual variability in the distribution of nutrients and chlorophyll *a* across the Gulf of Alaska shelf: 1998 – 2000. *Deep Se Res., Pt. II*, 52(1-2): 193-216.
- Coyle, K.O., Cheng, W., Hinckley, S., Lessard, E.J., Whitedge, T., Hermann, A.J., Hedstrom, K., 2012. Model and field observations of effects of circulation on the timing and magnitude of nitrate utilization and production on the northern Gulf of Alaska shelf. *Prog. Oceanogr.* 103, 16-41.
- Danielson, S., T. Weingartner, K. Hedstrom, K. Aagaard, R. Woodgate, E. Curchitser, and P. Stabeno. 2014. Ekman transport, continental shelf waves, and variations of the Pacific-Arctic sea surface height gradient: Coupled wind-forced controls of the Bering-Chukchi shelf circulation and the Bering Strait throughflow. *Progr. Oceanogr.*, 125: 40 – 61.
- Durack, P. J. and S. E. Wijffels. 2010. Fifty-year trends in global ocean salinities and their relationship to broad-scale warming. *J. Clim.* 23 (16): 4342-4362.
- Francis, R. C. and S. R. Hare. 1994. Decadal scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. *Fish. Oceanogr.*3: 279-291.
- Hare, S. R. and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Prog. Oceanogr.* 47: 103–145
- Hare, S.R., Mantua, N.J., Francis, R.C., 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. *Fisheries* 24, 6-14.
- Janout, M. A., T. Weingartner, P. Stabeno. 2013. Air-sea and oceanic heat flux contributions to the heat budget of the northern Gulf of Alaska shelf. 2013. *J. Geophys. Res.*, 118, doi:10.1002/jgrc.20095.

- Janout, M.A, T. J. Weingartner, T. Royer, and S. Danielson. 2010. On the nature of winter cooling and the recent temperature shift on the northern Gulf of Alaska shelf, *J. Geophys. Res.*, 115, C05023, doi:10.1029/2009JC005774.
- Lavaniegos, B.E., Ohman, M.D., 2007. Coherence of long-term variations of zooplankton in two sectors of the California Current System. *Prog. Oceanogr.* 75, 42-69.
- Mackas, D.L., Goldblatt, R., Lewis, A.G., 1998. Interdecadal variation in developmental timing of *Neocalanus plumchrus* populations at Ocean Station P in the subarctic North Pacific. *Can. J. Fish. Aquat. Sci.* 55, 1878-1893.
- Mackas, D.L., Peterson, W.T., Zamon, J.E., 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental margins of British Columbia and Oregon. *Deep-Sea Res. II.* 51, 875–896.
- McGowan, J. A., Cayan, D. R., & Dorman, L. M. 1998. Climate–ocean variability and ecosystem response in the Northeast Pacific. *Science*, 281: 210–217
- Musgrave, D. L., M. J. Halverson, and S. W. Pegau. 2013. Seasonal surface circulation, temperature, and salinity in Prince William Sound, Alaska. *Cont. Shelf Res.*, 53: 20 – 29.
- Neal, E. G., E. Hood, and K. Smikrud. 2010. Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophys. Res. Lett.*, 37, L06404, doi: 10.1029/2010GL042385.
- Royer, T. C., 1975. Seasonal variations of waters in the northern Gulf of Alaska, *Deep Sea Res.*, 22, 403-416.
- Royer T. C. 1982, Coastal freshwater discharge in the Northeast Pacific *J. Geophys. Res.* 87: 2017–2021.
- Royer, T. C. and C. E. Grosch. 2006. Ocean warming and freshening in the northern Gulf of Alaska. *Geophys. Res. Lett.* 33, L16605, doi:10.1029/2006GL026767.
- Strom, S. L., M. B. Olson, E. L. Macri, and C. W. Mordy. 2007. Cross-shelf gradients in phytoplankton community structure, nutrient utilization, and growth rate in the coastal Gulf of Alaska. *Mar. Ecol. Progr. Ser.*, 328: 75 – 92.
- Weingartner, T.J., *The Physical Environment of the Gulf of Alaska* (Section 2.2, p 12 – 47), IN: *Long-Term Ecological Change in the Northern Gulf of Alaska*, edited by R. B. Spies, Elsevier B.V., Amsterdam, 589 p., 2007
- Weingartner, T.J., S. Danielson, and T. C. Royer. 2005. Freshwater Variability and Predictability in the Alaska Coastal Current *Deep-Sea Res.*, 52: 169 – 192.
- Weingartner, T.J., K. Coyle, B. Finney, R. Hopcroft, T. Whitedge, R. Brodeur, M. Dagg, E. Farley, D. Haidvogel, L. Haldorson, A. Hermann, S. Hinckley, J. Napp, P. Stabeno, T. Kline C. Lee, E. Lessard, T. Royer, S. Strom. 2002. The Northeast Pacific GLOBEC Program: Coastal Gulf of Alaska, *Oceanogr.*, 15: 48 – 63

RESEARCH SUMMARY: LONG-TERM MONITORING OF OCEANOGRAPHIC CONDITIONS IN THE ALASKA COASTAL CURRENT FROM HYDROGRAPHIC STATION GAK 1

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The Alaska Coastal Current (ACC) circumscribes the entire inner shelf of the Gulf of Alaska. Its mean and varying properties reflect the spatially and temporally integrated forcing due to winds, coastal discharge, and air-sea heating and cooling. The current originates on the British Columbian shelf, substantial portions of it circulate through Prince William Sound and its waters feed lower Cook Inlet and Kachemak Bay before flowing southwestward through Shelikof Strait. Hydrographic station GAK 1, at the mouth of Resurrection Bay, has been shown to be an excellent proxy for the temperature and salinity properties of the ACC (Weingartner et al. 2005). Trends and anomalies at this station are also correlated with those over the mid- and outer shelf, although in general the anomaly magnitudes are larger within the ACC than farther offshore.

Hydrographic measurements at GAK 1 began in 1970. Initially the sampling was opportunistic, became more regular in the 1980s and 1990s, and then systematic beginning in 1997 with EVOSTC support. Since 1997 the sampling protocol has included both quasi-monthly conductivity-temperature versus depth (CTD) casts and hourly temperature and salinity measurements obtained by moored instruments at 6 depths distributed over the water column. GAK 1 is the *only station* in the Gulf of Alaska that measures both salinity and temperature over the 250 m deep water column. Over the years, data from GAK 1 has been used in over 35 scientific investigations addressing topics in physical and biological oceanography relevant to fisheries management (see GAK 1 website: http://www.ims.uaf.edu/GAK_1/ for partial listing of publications. Note additional publications, of which we are unaware, may also have used these data). This report briefly summarizes the available time series based on both sampling protocols and re-examines a number of trends last reported by Royer and Grosch (2005) that covered the period from 1970 to 2005.

The annual cycles are clearly evident in Figure 2-4a and Figure 2-5a. Figure 2-6 shows an example of the annual cycle as obtained from the GAK 1 mooring from April 2011 – March 2012. These time series also include the corresponding time series for density (expressed as sigma-t), in which it is evident that density variations mirror salinity changes.

Note that over the 1970 – 2014 period, the coldest waters (Figure 2-4b) occurred through the first pentad of the 1970s. Thereafter temperatures warmed in association with the mid-1970s regime shift (Mantua et al. 2000) cooled through much of 2007-2012 and warmed in 2013-2014. The only other noteworthy cooling events occurred in 1991, 2007-08, and 2009-10 and 2012. These latter cooling events were mainly confined to the winter and early spring in contrast to the early 1970s, when the anomalies appeared to be persistent over several years.

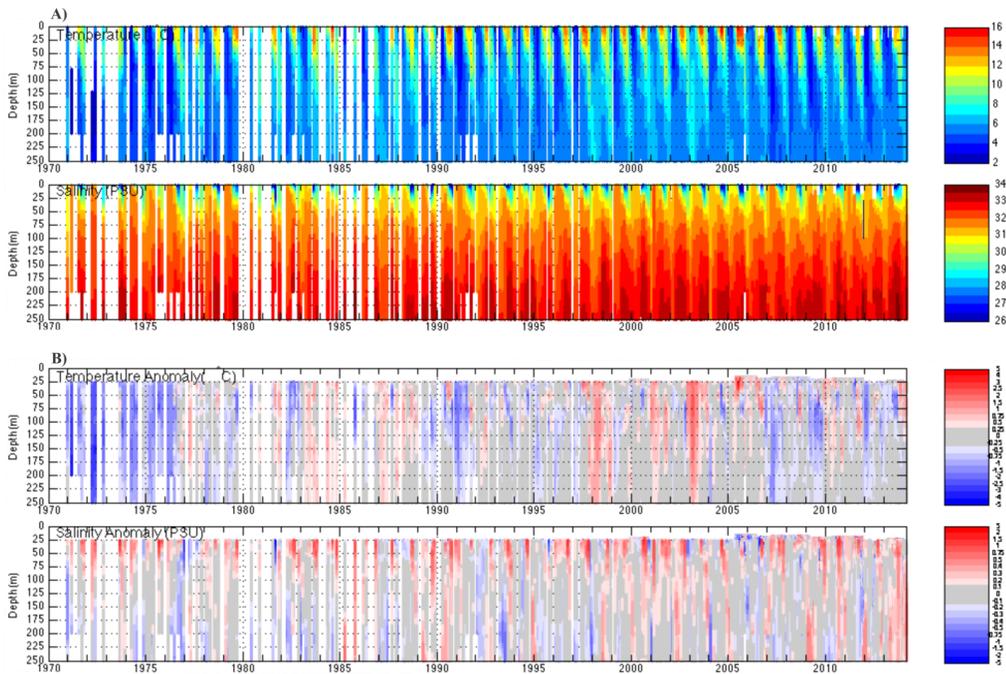


Figure 2-4. A) Time series of monthly temperature and salinity obtained from GAK 1 CTD casts since 1970. Density profiles are available at [http://www.ims.uaf.edu/GAK 1/](http://www.ims.uaf.edu/GAK1/). B) Corresponding time series of monthly anomalies based on the 2000 – 2014 mooring data shown in Figure 2

Analysis of long-term trends (Figure 2-7) indicate that the GOA shelf has warmed by approximately $1\text{ }^{\circ}\text{C}$ over the past 44 years in the upper 100 m and by approximately $0.6\text{ }^{\circ}\text{C}$ between 100 and 200 m. Salinity has decreased by approximately 0.6 at the surface and by approximately 0.2 over the upper 100m. Note that the temperature trends are slightly lower than those reported by Royer and Grosch (2006). The differences are associated with the anomalous cooler winters of 2007-08, 2009-10, and 2012. In contrast, the salinity between 100 and 200 m depth has increased by approximately 0.1 . These contrasting changes in salinity imply that the vertical stratification of the water column has increased substantially over the past 44 years.

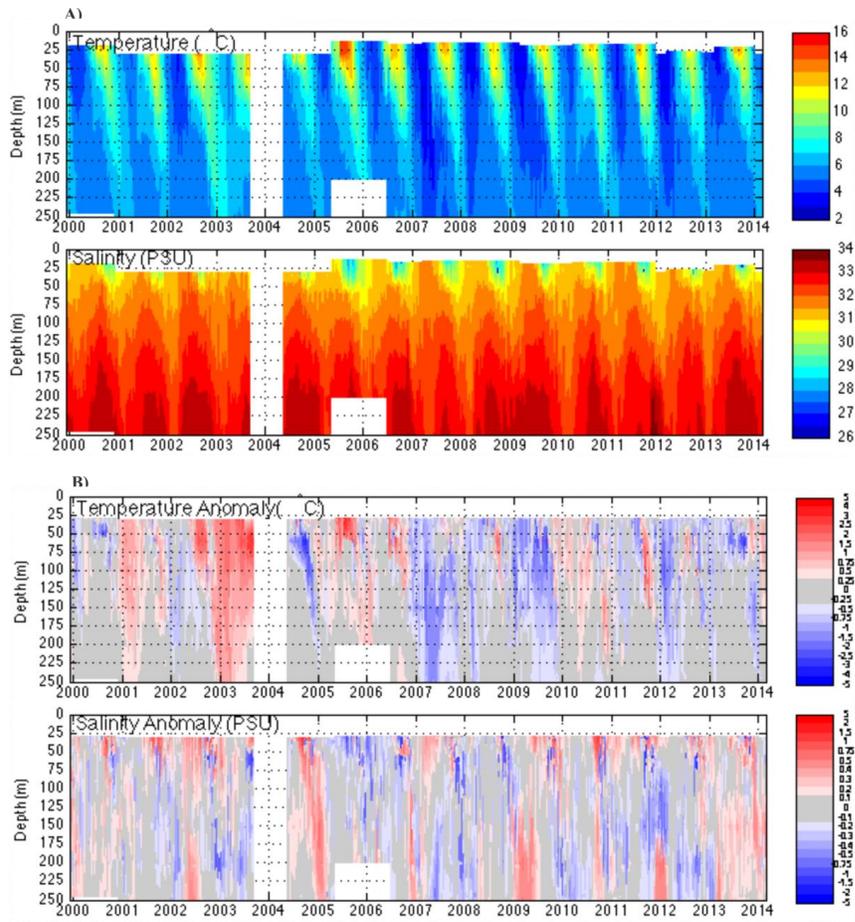


Figure 2-5. A) Time series of daily temperature and salinity obtained from the GAK 1 mooring since 2000. B) Corresponding time series of anomalies obtained from the data in

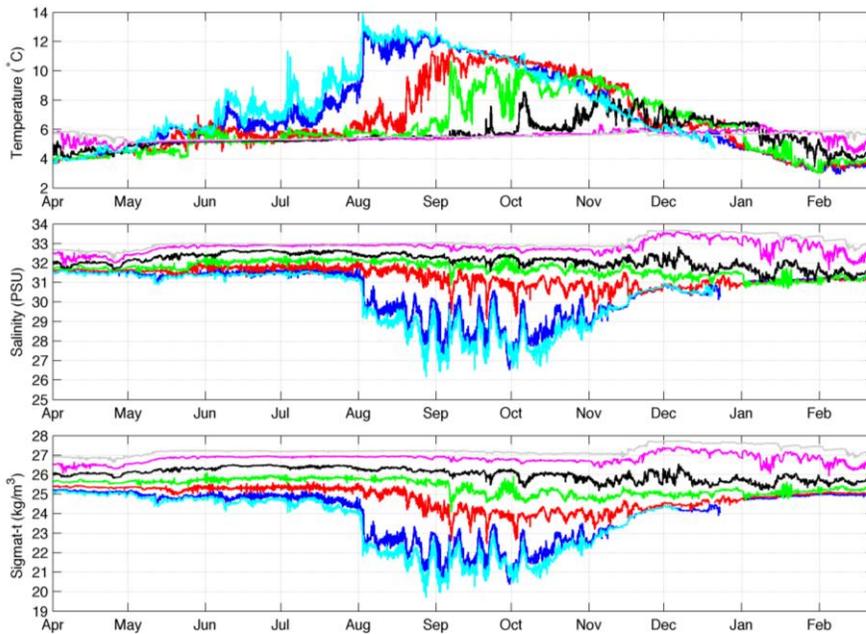


Figure 2-6. Time series of hourly temperature (top), salinity (middle), and density (sigma-t; bottom) at 20 m (cyan), 30 m (blue), 60 m (red), 100 m (green), 150 m (black), 200 m (magenta), and 250 m (gray) depths from April 2011 to March 2012.

The stratification increase is in part due to the long-term trend toward increasing discharge (Hill et al. submitted). The deep salinity increase is somewhat surprising, but may be related to three possible mechanisms. That increase reflects exchanges with the basin, which occurs most prominently on an annual basis (Figure 2- 6) with the seasonal relaxation in alongshore wind stress (Royer, 1975; Weingartner et al., 2005). (2011-2012). We therefore examined the long-term trend in alongshore and cross-shore wind stresses. There is no trend in the alongshore wind stress component (Figure 2-8, top panel), and so we reject the hypothesis that the deep salinity increase is associated with changes in the alongshore wind stress. Of interest is that the cross-shore stress shows a significant decrease (becomes more northerly; Figure 2-8, middle panel). This change is most prominent after 1995 and is associated with a change in the position of the Aleutian Low (Danielson et al. 2014).

Two other possible mechanisms are responsible for the deep salinity increase. The first is simply associated with a decrease in vertical mixing efficiency. This would be brought about by an increase in discharge (as observed) and/or a change in wind speeds. In particular vertical mixing is proportional to wind speed cubed. As evident in Figure 2-8 (bottom panel), this variable has significantly decreased through time so that wind-driven mixing has decreased over the shelf in the past 40 years. The last mechanism potentially involved in the deep salinity increase is a change in the salinity of the waters bathing the outer edge of the GOA continental slope. Such changes could be assessed using the plethora of Project ARGO floats that have been deployed in the Gulf of Alaska basin over the past 15 years. This effort is beyond the scope of the present work, but worth undertaking in the future.

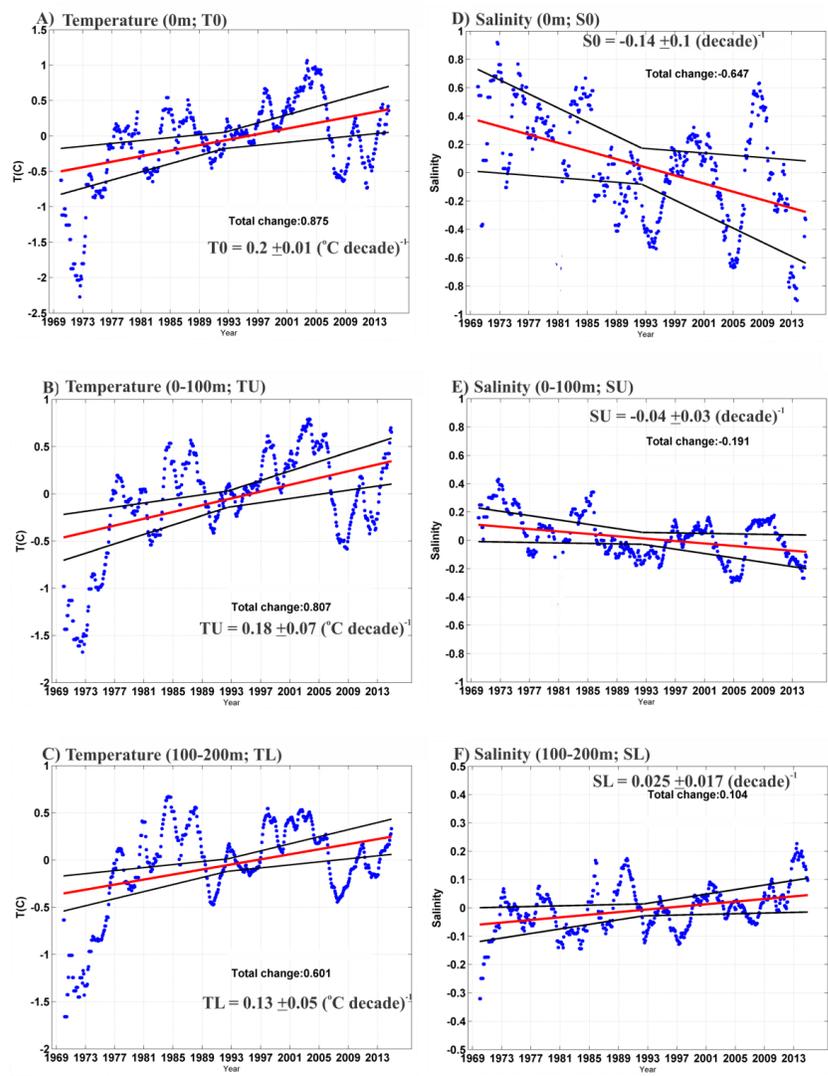


Figure 2-7. Long-term linear trends in monthly anomalies of temperature at the a) surface (T0), b) 0 – 100m (TU), and c) 100 – 200m (TL). Long-term linear trends in monthly anomalies of salinity at the d) surface (S0), e) 0 – 100m (SU), and f) 100 – 200m (SL). All regressions are significant at the 95% level, except for SU, which is significant at the 90% level. Blue dots are the monthly anomalies smoothed with a 25-month running mean.

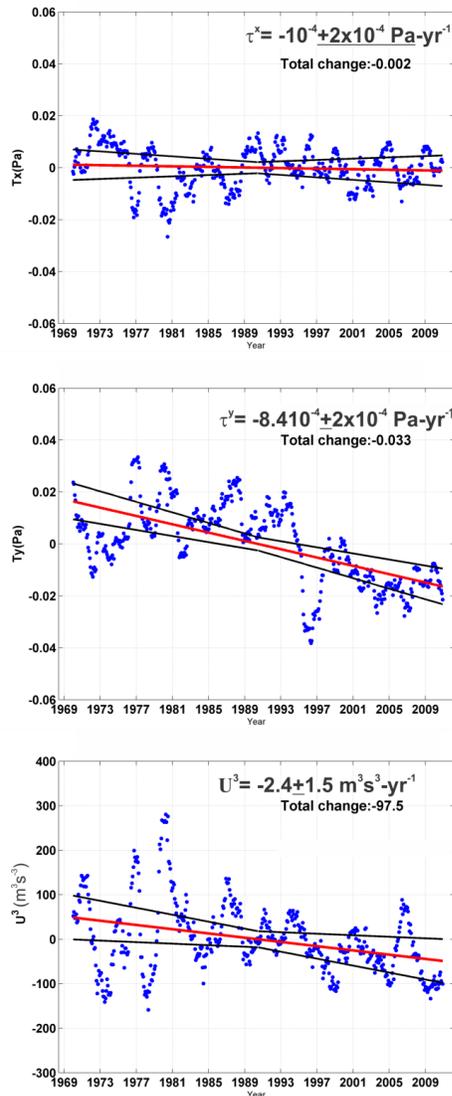


Figure 2-8. Long-term linear trends in monthly anomalies of the along- $(\tau^x$; top panel) and cross-shore $(\tau^y$; middle panel) wind stresses and wind speed cubed, U^3 (bottom panel). All regressions are significant at the 95% level, except for τ^x , which is not significant. Blue dots are the monthly anomalies after smoothing with a 13-month running mean.

The 25-month running means of the monthly anomalies shown in Figure 2-7 indicate substantial low-frequency variability in the hydrographic properties. Variability at these long time scales is most likely due to basin-wide, hemispheric or global processes. Several decadal-scale fluctuations in climate have been previously linked to low-frequency hydrographic forcing in the Gulf of Alaska. These include the

Pacific Decadal Oscillation (PDO, Mantua et al. 1997), the El Niño and La Niña events of the equatorial Pacific as gauged by the Southern Oscillation (SOI) index. The PDO is the first empirical orthogonal mode of North Pacific sea surface temperature anomalies (SSTA). Its characteristic signal is approximately decadal and includes out-of-phase SSTA between the northwestern and northeastern Pacific Ocean. Fluctuations in the SSTA patterns also coincide with fluctuations in the intensity and position of the Aleutian Low. El Niño and La Niña events are initiated in the equatorial Pacific, but are linked by atmospheric and oceanic teleconnections to the North Pacific Ocean and Gulf of Alaska. The North Pacific Gyre Oscillation (NPGO) is the second empirical orthogonal mode in sea surface height variability Di Lorenzo et al. (2008) and is significantly correlated with salinity, nutrients and chlorophyll-a variations in the California Current and the Gulf of Alaska basin (specifically along Line P). Royer and Grosch (2006) previously related GAK 1 hydrographic variability to the PDO and SOI. We updated their results and find that the PDO index explains approximately 38% of the temperature variance, but less than 15% of the salinity and discharge variance. In all cases, the maximum correlation occurred with the PDO index leading these variables by from two to three months. The SOI index explains approximately 20% of the temperature variance and leads the temperature signal by from eight to nine months. The SOI index is maximally correlated with salinity when leading by six to seven months, but explains less than 10% of the salinity variability. The NPGO was uncorrelated with either temperature or salinity. This last result suggests that the inner shelf of the GOA is not responding to the GOA basin signatures associated with the NPGO.

In summary the GAK 1 data collected over the past ten years, supports previous findings of a long-term trend in warming over the GOA shelf, an increase in deep (> 100 m) salinities and a decrease in upper ocean (0 – 100 m) salinities. The latter finding is in agreement with the long-term trend toward increasing discharge throughout the GOA. These results have strong biological implications. A warming environment should affect metabolic activities of a host of marine species, although it remains unclear what the ramifications of these changes will be on the ecosystem as a whole. Of particular significance is that the GOA shelf is undergoing a substantial change toward increasing stratification. This increase appears to be a response to surface freshening due to increased coastal freshwater discharge, a reduction in wind mixing, and an increase in deep salinity. The reasons for the deep salinity increase are uncertain. The increase may simply be related to a decrease in vertical mixing efficiency due to the combined increase in discharge and decrease in wind speed. It does not appear to be related to changes in the along-shore wind stress that would induce changes in the position of the shelf break front that separates fresher shelf waters from saltier slope waters. There may be other pathways by which slope waters intrude on the shelf involving topographically-induced exchanges, but these potential mechanisms are not obvious. Finally, the deep salinity increase could be related to increasing salinities within the GOA basin and along the GOA continental slope but the mechanisms remain to be explored.

The sustained change in stratification has potentially tremendous implications on the GOA marine ecosystem. This change could not have been detected without the long-term (now approaching 44 years) monitoring at GAK 1.

References

Di Lorenzo E., Schneider N., Cobb K. M., Chhak, K., Franks P. J. S., Miller A. J., McWilliams J. C., Bograd S. J., Arango H., Curchister E., Powell T. M. and P. Rivere, 2008: North Pacific Gyre

Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.*, 35, L08607, doi:10.1029/2007GL032838.

Mantua, N.J. and S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78, pp. 1069-1079.

Royer, T. C. and C. E. Grosch. 2006. Ocean warming and freshening in the northern Gulf of Alaska. *Geophysics Research Letters* 33, L16605. DOI: 10.1029/2006GL026767

THE SEWARD LINE: 17 YEARS OF PATTERN AND VARIABILITY IN THE COASTAL GULF OF ALASKA.

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The Seward Line (Sousa et al. accepted) now represents the most detailed multi-disciplinary long-term oceanographic sampling program in the northern Gulf of Alaska, with occupation occurring early each May and mid-September. It complements, and intertwines with Gulf Watch Alaska programs that focus on Cook Inlet and Kachemak Bay (Doroff and Holderied), the Alaska Coastal Current (Weingartner), Prince William Sound (Campbell), and still broader across the Gulf of Alaska (Batten). Among these projects, it is the only one that measures carbonate chemistry (Ocean Acidification; Evans and Mathis, 2013; Evan et al. 2014). The Seward Line monitoring has allowed us to recognize that the Gulf of Alaska shelf undergoes multi-year periods of warm and cold springs (Figure 2-9). It allows us to capture extreme events such as the cold winters (Janout et al. 2010) or ocean warming as occurred in 2014, where temperatures at some locations were as much as 2.6°C above the long-term mean (Figure 2-10). The Seward Line time series is finally approaching sufficient duration that we might soon extract longer-term trends underlying these shorter-term cycles, as is now possible for GAK 1 and Prince William Sound.

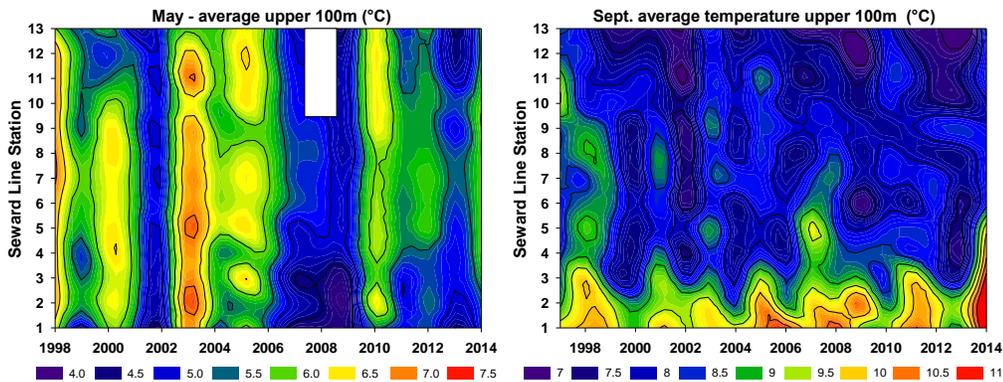


Figure 2-9. The average temperature measured in the upper 100 of the Seward Line in early May and mid-September, showing cold and warm spring periods and general lack thereof in late summer.

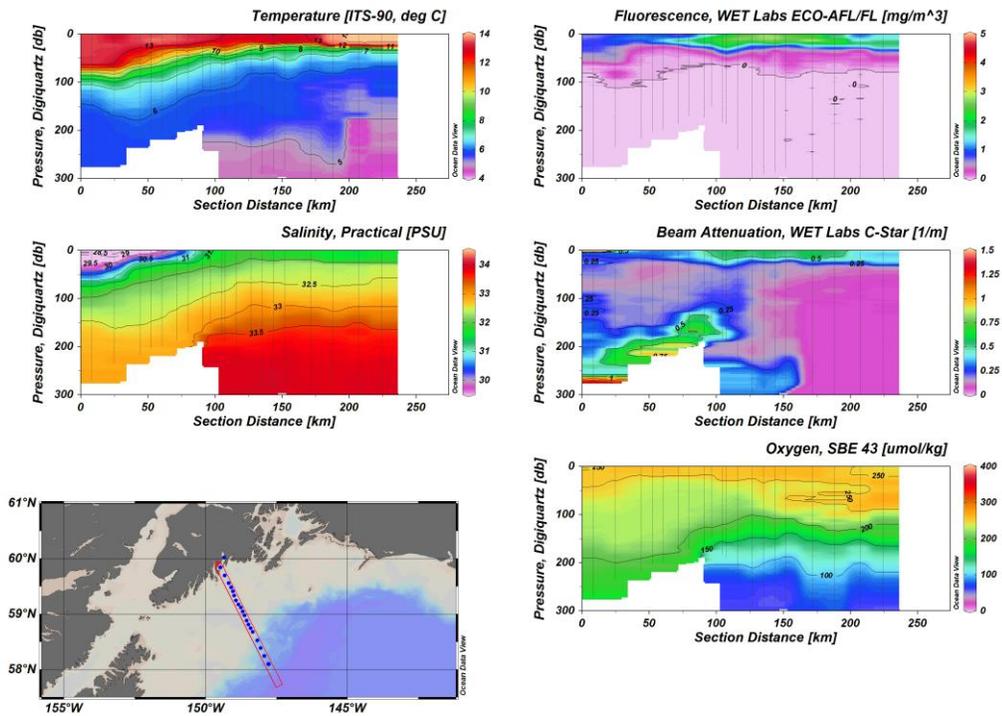


Figure 2-10. Oceanographic sections along the Seward Line in mid-September 2014, highlighting the extreme surface temperatures. Also notable are the freshwater signal of the Alaska Coastal Current, the subsurface chlorophyll maximum as revealed by Fluorescence and light transmission/attenuation, and the typical depletion of oxygen that occurs with depth, particularly in offshore waters

The Seward Line is also now of sufficient duration that we can establish the long-term mean and trends of biological components, such as key zooplankton species (Figure 2-11). The abundance of some of these species, such as *Neocalanus* copepods (Mundy et al. 2010) and pteropods (Doubleday and Hopcroft, in press), are correlated to the survival of commercial species such as pink salmon. We are now closer to defining the environmental windows preferred by individual species (Strom et al. 2007; Sousa et al., accepted), establishing which species have flexible versus narrow niches. Concurrently, we are exploring the gradients in community structure that occur across the shelf and into Prince William Sound (Figure 2-12). Inshore-offshore gradients are most apparent on the horizontal axis, while scatter reflects interannual variability driven by other environmental factors. These observations, in conjunction with broader-scale efforts such as NPRB's Gulf of Alaska project, form the foundation for Gulf-wide ecosystem modeling (Coyle et al. 2012, 2013) and examining the importance of various environmental drivers.

By merging the data from the Seward Line with other oceanographic and plankton time series in the environmental drivers component of the Gulf Watch Alaska program, we seek to explore seasonal and interannual linkages between nearshore, shelf and offshore waters, as well as the more local nuances that shape differences in the physical, chemical and biological environments. Aligning measurements of

temperature and salinity are relatively straight-forward, as are measurements of nutrients and chlorophyll where available. Taking advantage of integration opportunities within the Gulf Watch Alaska program, we are assessing the impact of differences in zooplankton collection methods between investigators (see Skjoldal et al. 2013), and the extent to which interannual signals in data are in phase, even if different in their absolute baselines.

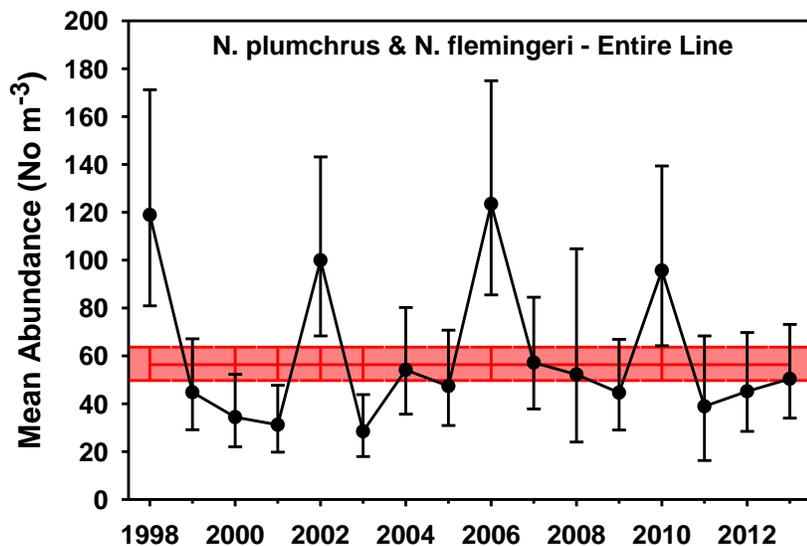


Figure 2-11 Variability in the abundance of a Gulf of Alaska's keystone copepod, *Neocalanus plumchrus/flemingeri*, along the Seward Line during May. The red bar establishes the long-term mean and its 95% confidence interval, compared to the annual observation along with its 95% confidence interval.

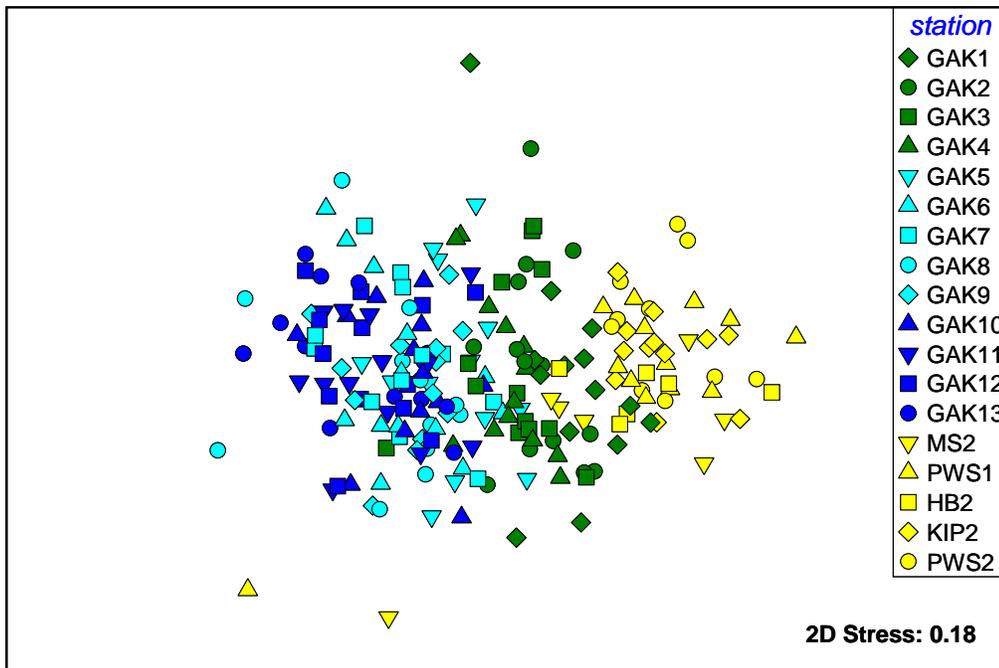


Figure 2-12. Non-parametric multidimensional scaling of May zooplankton community structure, where distance between samples reflects their similarity. Prince William Sound waters (yellow) through the nearshore GAK stations (green), through midshelf (light blue), to offshore waters (dark blue). Data covers the period 1998-2012.

References

- Coyle, K.O., Gibson, G.A., Hedstrom, K., Hermann, A.J., Hopcroft, R.R., 2013. Zooplankton biomass, advection and production on the northern Gulf of Alaska shelf from simulations and field observations. *J. Mar. Sys.* 128, 185-207.
- Coyle, K.O., Cheng, W., Hinckley, S., Lessard, E.J., Whitley, T., Hermann, A.J., Hedstrom, K., 2012. Model and field observations of effects of circulation on the timing and magnitude of nitrate utilization and production on the northern Gulf of Alaska shelf. *Prog. Oceanogr.* 103, 16-41.
- Doubleday, A.J., Hopcroft, R.R., *in press*. Seasonal and interannual patterns of larvaceans and pteropods in the coastal Gulf of Alaska, and their relationship to pink salmon survival *J. Plankton Res.* doi:10.1093/plankt/fbu092
- Evans, W., Mathis, J.T., 2013. The Gulf of Alaska coastal ocean as an atmospheric CO₂ sink. *Cont. Shelf Res.* 65, 52-63.
- Evans, W., Mathis, J.T., Cross, J.N., 2014. Calcium carbonate corrosivity in an Alaskan inland sea. *Biogeosci.* 11, 365-379.

- Evans, W., Mathis, J.T., Winsor, P., Whitlege, T., Statscewich, H., 2013. A regression modeling approach for studying carbonate saturation states on the northern Gulf of Alaska shelf. *J. Geophys. Res.* 118, 476-489.
- Janout, M.A., Weingartner, T.J., Royer, T.C., Danielson, S.L., 2010. On the nature of winter cooling and the recent temperature shift on the northern Gulf of Alaska shelf. *J. Geophys. Res.* 115, C05023.
- Mundy, P., Allen, D., Boldt, J.L., Bond, N.A., Dressel, S., Farley Jr., E., Hanselman, D., Heifetz, J., Hopcroft, R.R., Janout, M.A., Ladd, C., Lam, R., Livingston, P., Lunsford, C., Mathis, J.T., Mueter, F., Rooper, C., Sarkar, N., Shotwell, K., Sturdevant, M., Thomas, A.C., Weingartner, T.J., Woodby, D., 2010. Status and trends of the Gulf of Alaska Coastal region, 2003-2008. In: McKinnell, S.M., Dagg, M. (Eds.), *The North Pacific Ocean; status and trends, 2003-2008*. PICES Special Publication 4.
- Skjoldal, H.R., Wiebe, P.H., Postel, L., Knutsen, T., Kaartvedt, S., Sameoto, D.D., 2013. Intercomparison of zooplankton (net) sampling systems: Results from the ICES/GLOBEC sea-going workshop. *Prog. Oceanogr.* 108, 1-42.
- Sousa, L., Coyle, K.O., Barry, R.P., Weingartner, T.J., Hopcroft, R.R., *accepted*. Climate-related variability in abundance of mesozooplankton in the northern Gulf of Alaska 1998-2009. *Deep-Sea Res. II*.
- Strom, S.L., Olson, M.B., Macri, E.L., Mordy, C.W., 2007. Cross-shelf gradients in phytoplankton community structure, nutrient utilization, and growth rate in the coastal Gulf of Alaska. *Mar. Ecol. Prog. Ser.* 328, 75-92.

LINKING VARIABILITY IN OCEANOGRAPHIC PATTERNS BETWEEN NEARSHORE AND SHELF WATERS ACROSS THE GULF OF ALASKA

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Introduction

Marine ecosystems in the northern Gulf of Alaska can be broadly divided into pelagic and nearshore food webs, which are influenced by the along-shore oceanographic connection of the Alaska Coastal Current and by exchange of waters between large estuaries and the shelf. In the pelagic food web, primary production from phytoplankton is transferred through zooplankton and forage fish to larger fish species and marine mammals (Spies 2006). Ocean conditions drive the timing and magnitude of primary production through changes in light, temperature, nutrients, and stratification, which are influenced by local (such as upwelling and topographic wind forcing) and basin-scale (such as the Aleutian Low wind circulation) processes (Mundy 2005). The nearshore food web includes primary production from kelps and seagrass, as well as phytoplankton, with a transfer of energy to top predators through vertebrates such as fish and invertebrates such as clams, mussels and urchins. Macroalgae growth is dependent on light, temperature and nutrients and invertebrate growth is dependent on temperature and circulation-driven food supply, with the environmental conditions again influenced by both local (e.g. snowpack and glacial melt runoff) and large-scale processes.

Long-term monitoring data collected under the Environmental Drivers component of the Gulf Watch Alaska ecosystem monitoring program is being used to assess the relative influence of local and basin-scale forcing on ocean conditions and the food webs that depend on the marine environment. Monitoring conducted at multiple sites within the *Exxon Valdez* Oil Spill (EVOS)-affected region is also being used to determine if changes in shelf waters and plankton in the northern Gulf of Alaska measured at the Gulf of Alaska 1 mooring (GAK 1) (Weingartner project), Seward Line (Hopcroft project) and cross-shelf continuous plankton recorder transects (Batten project) are synchronous with near-shore conditions measured in lower Cook Inlet (Doroff and Holderied project) and Prince William Sound (Campbell project). We are particularly interested in how near-shore conditions reflect the significant inter-annual variability in the North Pacific Ocean associated with major climate patterns such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), since North Pacific ecosystem “regime shifts” have been associated with environmental changes at that scale (Mantua et al. 1997).

Both Prince William Sound and Cook Inlet are large Gulf of Alaska estuaries that are connected by the Alaska Coastal Current, influenced by freshwater input (precipitation, snowpack and glacier melt), and experience upwelling of waters from the adjacent shelf. Cook Inlet is distinguished by stronger tidal currents and associated complex oceanographic fronts that are linked to bathymetry and freshwater runoff (Okkonen and Howell 2003, Okkonen et al. 2009). As part of Gulf Watch Alaska monitoring in lower Cook Inlet and Kachemak Bay, we are conducting repeated shipboard transects of vertical oceanographic profile stations and plankton sampling, which are combined with longer time series from the Kachemak Bay National Estuarine Research Reserve (KBNERR) water quality monitoring stations at the Seldovia and Homer harbors (for locations see map in Figure 2-3 in the Chapter 2 introduction). For an initial assessment of estuary-shelf linkages over longer time periods, we compare temperature data between the KBNERR water quality station (2004-present) and GAK1 mooring. To examine patterns along the Gulf

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of Alaska coast, we show longer time series of near-shore temperature from the NOAA National Water Level Observation Network (NWLON) stations at the Cordova, Seldovia, Seward and Kodiak Alaska harbors in the EVOS-affected region, as well as from stations at Yakutat and Ketchikan, which are upstream in the Alaska Coastal Current from the EVOS region (Figure 2-14).



Figure 2-13 Cook Inlet oceanographic and plankton sampling stations. Green dots indicate CTD station locations, with plankton sampling also conducted at stations with red dots (3 per transect). The KBNERR water quality stations are located in Kachemak Bay at the Seldovia and Homer harbors and in Bear Cove in summer months.



Figure 2-14 Locations of selected NOAA National Water Level Observation Network (NWLON) station sites in the Gulf of Alaska and the National Estuarine Research Reserve System-wide Monitoring Program (SWMP) stations in Kachemak Bay at Seldovia and Homer (red dots). Shaded blue bathymetry shows the continental shelf, along which flows the Alaska Coastal Current.

Study Area

Cook Inlet is a large tidal estuary that extends over 350 km southwest from Anchorage to Cape Douglas and is separated from the Kodiak archipelago by Shelikof Strait. Ocean circulation in lower Cook Inlet is influenced by strong tides, freshwater runoff from rivers, snowpack and glacier meltwater, wind and marine intrusions of the Alaska Coastal Current (ACC). The ACC flows from east to west along the northern Gulf of Alaska coast as the northern arm of the wind-driven sub-polar gyre, reinforced by input of freshwater from heavy precipitation along the mountainous coasts of the Pacific Northwest, British Columbia and southeast and southcentral Alaska (see Hopcroft et al. Chapter 2 Introduction of this report). As the ACC moves into the mouth of Cook Inlet it is also forced up vertically, resulting in upwelling of nutrient rich deep water (Muench et al. 1978). The bathymetry of the region is shaped primarily by extensive glaciation during the last ice age, river flow, and sediment transport.

Most of Kachemak Bay has been designated as the KBNERR, and it is the largest and the only fjord estuary in the NERR system. Kachemak Bay is also designated as an Alaska State critical habitat area and a NOAA Habitat Blueprint focus area. Cook Inlet and Kachemak Bay experience large influxes of freshwater during the spring and summer due to increases in precipitation and glacial melt. This freshwater influx results in seasonal stratification with warmer, fresher water on the surface during warmer months, dominated by the buoyancy flux associated with freshwater input (AOOS 2005). Cook Inlet also experiences one of the largest tidal ranges in the world averaging 5.5m with a maximum range

of 8.5m in Kachemak Bay (KBNERR 2010). Day length (light availability) varies seasonally from 19 hours in the summer to less than six hours during the winter.

Results and Conclusions

We are fortunate to have captured a range of different forcing conditions (near record versus normal snow pack and normal summer precipitation/temperature versus dry/warm summer conditions) in the first years of the project (2012-2014). The KBNERR water quality station time series (2004-present) also covers two periods of generally warmer temperatures (2004-2005 and 2013-2014), separated by a period of relatively cooler temperatures (2006-2012). The Cook Inlet oceanographic data also support other Gulf Watch Alaska funded projects: Kachemak Bay nearshore monitoring (Konar and Iken), and U.S. Fish and Wildlife Service seabird and marine mammal observers who are part of the pelagic monitoring component (Kuletz).

Long-term data comparison at nearshore stations

For an initial comparison of longer-term, temperature patterns along the GOA coast, a visual assessment of broad-scale patterns was made at shore stations within and outside the Gulf Watch Alaska region. Near-surface water temperature time series were constructed from NOAA NWLON (tide gauge) station data by compiling data from published reports of monthly anomalies (C&GS 1961), hardcopy station data sheets from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) and the station data on the CO-OPS data portal (1994-present at www.tidesandcurrents.noaa.gov). Monthly anomalies were created for all months with sufficient data (>600 data points), against means calculated for nearly continuous portions of each time series and normalized by calculating standard deviations. Time series are compared here for selected months from five tide stations (Figure 2-14) extending from west to east along the coast: Kodiak in southcentral Alaska (1950-2013); Seldovia in southcentral (1964-2013); Seward in southcentral (1925-1939, 1944-2013); Ketchikan in southeast (1921-1984 and 1994-2013); and Yakutat in the northern GOA (1940-1984 and 1994-2013).

Kodiak, Seldovia and Seward are within the EVOS-affected region, while Yakutat and Ketchikan are east of the region. All stations are connected by the ACC. The main feature of interest was the period of the 1976 North Pacific regime shift. For January (Figure 2-15) there is a distinct transition from cooler to warmer anomalies at the Kodiak, Seldovia, and Seward stations, but not a clear signal for the Yakutat and Ketchikan stations. In March (Figure 2-16), the cool to warm transition is clear at all five stations, while in June it is consistent for all stations except Seward. Similarly the warm period in the early part of the 2000s is seen consistently for all three months at all stations, with the exception of Ketchikan in January and March and Seward in June. While these results are obviously influenced by differences in the lengths of the data records, particularly for the Yakutat and Ketchikan stations, the linkages at decadal scales are striking. These time series will be incorporated into more detailed correlations with Gulf Watch Alaska data following additional quality control.

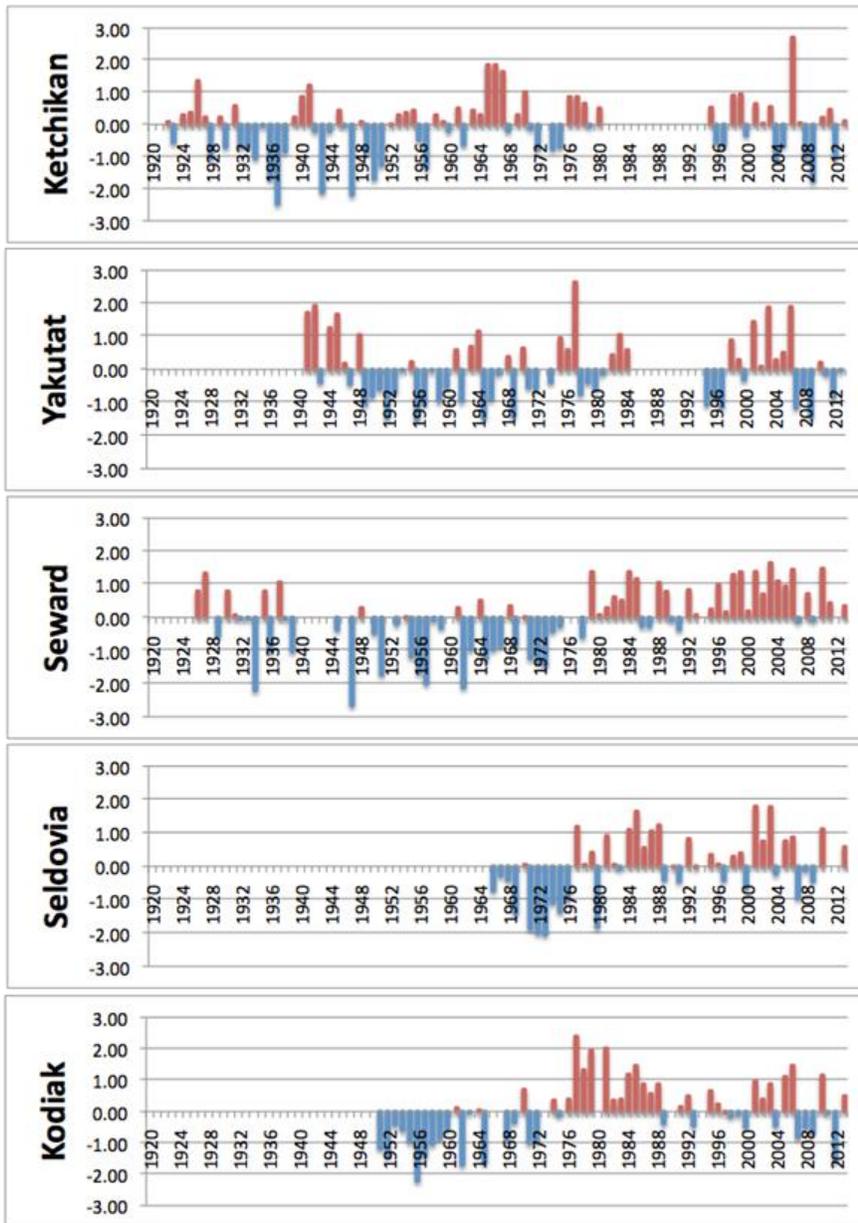


Figure 2-15 January water temperature anomalies at five NOAA water level stations. Years are shown on the x-axis (1920-2013) and standard deviation on the y-axis. Red colors indicate positive anomalies (warmer than average) and blue colors indicate negative anomalies (colder than average).

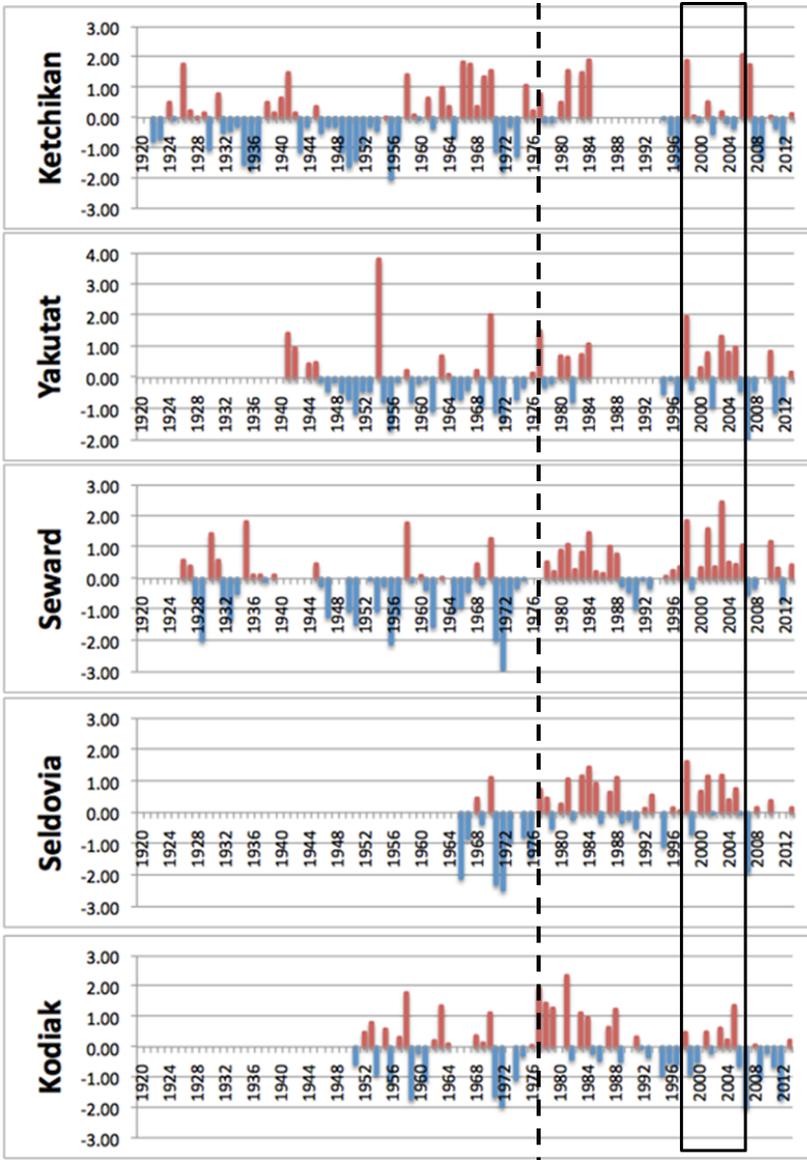


Figure 2-16 March water temperature anomalies at five NOAA water level stations. Years are shown on the x-axis (1920-2013) and standard deviation on the y-axis. Red colors indicate positive anomalies (warmer than average) and blue colors indicate negative anomalies (colder than average).

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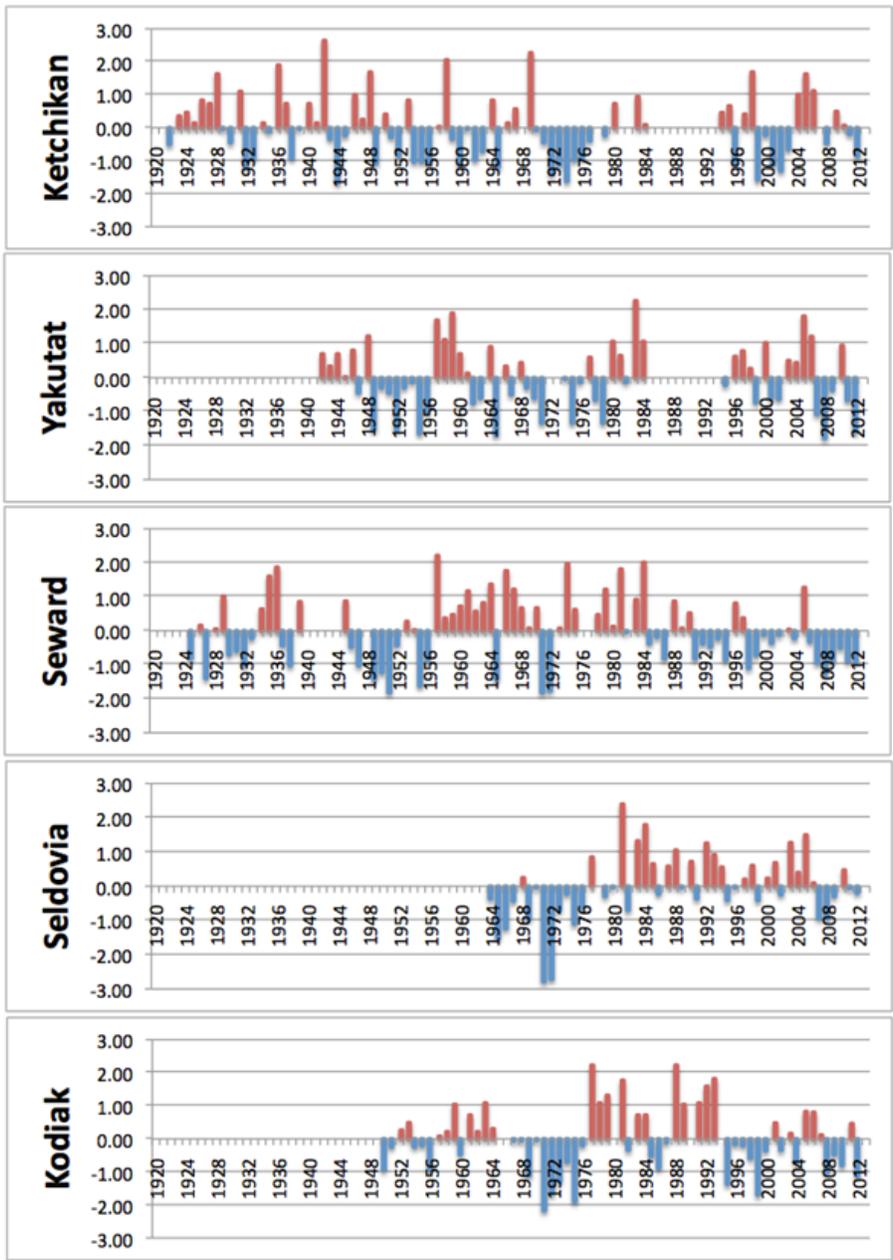


Figure 2-17 June water temperature anomalies at five NOAA water level stations. Years are shown on the x-axis (1920-2013) and standard deviation on the y-axis. Red colors indicate positive anomalies (warmer than average) and blue colors indicate negative anomalies (colder than average).

Linkages in estuary-shelf ocean conditions

The GAK 1 station data is described earlier in this chapter and includes both continuous data from six sensors on the mooring and approximately monthly vertical oceanographic profiles made with shipboard CTD measurements. As an initial comparison of inner shelf conditions to estuary conditions, we compare temperature data from the shallow GAK 1 mooring sensor at 25 meter (m) depth to the near surface Seldovia tide gauge data. Both time series are continuous, absent data gaps for sensor problems, and Seldovia's location in outer Kachemak Bay is expected to be more representative of oceanic conditions within the estuary than the inner bay water quality station at Homer Harbor. The tide gauge data was used for the initial assessment as it provides a longer time series (1964-present) than the KBNERR water quality station at the same location.

A comparison of time series plots from 1998-2011 for the 25 m depth at the GAK 1 mooring and at the Seldovia tide gauge is shown in Figure 2-18, top. As expected, there is close correspondence between annual cycles in the two time series, with relatively warmer summer temperatures at GAK 1 and colder winter temperatures at Seldovia. While the annual cycles are comparable, shorter period fluctuations are far less coherent. It also appears that temperatures at both locations generally increase at the same rate through spring, but that GAK 1 temperatures can rapidly increase in late spring. These rapid jumps are very likely associated with the along-shore advection of fronts, which may be considerably weakened in the tidally-mixed regimes offshore of and within lower Cook Inlet.

Monthly mean temperatures were calculated to compare seasonal patterns based on the GAK 1 mooring at 25 m depth (1998 – 2011), the GAK 1 CTD measurements at the surface (1995 – 2014), and the Seldovia tide gauges for the same time periods (Figure 2-18, bottom). Note first that the surface temperatures from the GAK 1 CTDs and Seldovia are in phase, with the warmest temperatures occurring in August and the coldest temperatures occurring in March. In contrast, the mean monthly values based on the 25 m depth moored record at GAK 1 indicate that the warmest temperatures occur in September, not August. This is a consequence of the seasonal cycle in surface heating and wind mixing over the shelf. At GAK 1 surface heating has begun to rapidly decrease in September and wind mixing (and the breakdown in stratification) has begun to increase. Both processes lead to a deeper mixed layer with cooling at the surface, but warming continuing at 25 m depth. The second point to note is that, throughout the year, surface and 25-m deep temperatures at GAK 1 are equal to or warmer than those at Seldovia. These differences are again related to the different forcing conditions (discussed above) at each site. This analysis does suggest that the inner shelf GAK 1 temperatures (at least on a monthly-averaged basis) are a reasonably good proxy for estuary conditions at Seldovia and vice versa.

We have also examined the coherence (correlation) between temperature fluctuations at the Seldovia tide gauge site and the shallow (25 m) mooring sensor at GAK 1. The calculations were based on a one-year comparison between the two sites. We find that coherence is generally low especially at shorter periods (< 30 days; Figure 2-19). At short periods the coherence squared

(which expresses the percentage of temperature variance at Seldovia explained by the GAK 1 record), is < 0.4 and often insignificant. This is not surprising given that lower Cook Inlet is subject to very different forcing conditions than the inner shelf, including much higher tides and tidal mixing than at GAK 1. In addition, the winds within the inlet and at the mouth of the inlet can be quite different in terms of both orientation and strength than at GAK 1. In winter, down inlet winds can also be substantially colder than those over the south Gulf coast and therefore induce considerably more cooling than at GAK 1. Finally, the mouth of the inlet is subject to topographically-induced upwelling associated with topographic steering as the ACC turns southward to enter Shelikof Strait. Each of these factors contributes at relatively short time periods to diminish the coherence in water properties between the two sites. As discussed below, there are also differences in sampling approaches between the two sites that contribute to the corrosion in coherence.

A more extensive examination of the coherence between these two sites is presently underway. This will entail examining the coherence seasonally based on approximately 10 years of time series between the KBNERR water quality monitoring station at Seldovia (shorter data record but better data quality than the tide gauge data) and GAK 1 mooring data. This analysis will explore whether or not the coherence relationship discussed above holds seasonally. At the moment the low coherence at short periods suggest considerable spatial heterogeneity in the water properties in the coastal GOA. These short period and short spatial scale differences have biological implications with respect to establishing conditions that may or may not be favorable to the timing of phytoplankton blooms and the development of zooplankton communities. They also imply that these spatial differences are likely to play a role in supporting the diversity of marine habitats throughout the GOA.

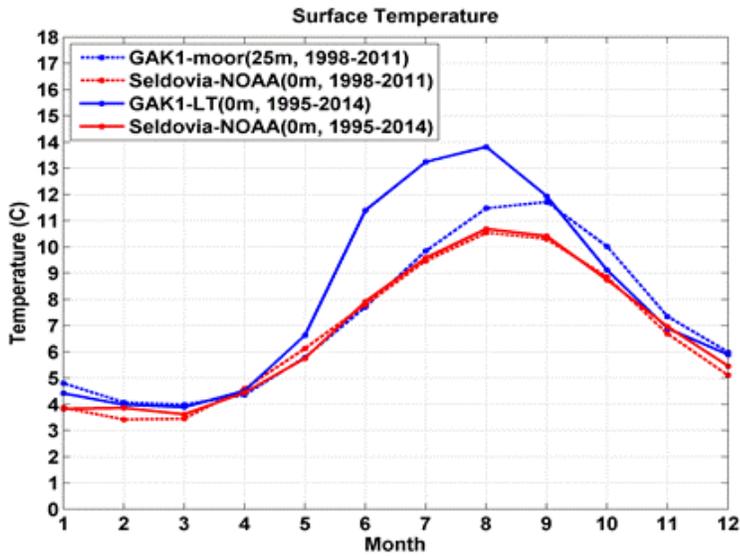
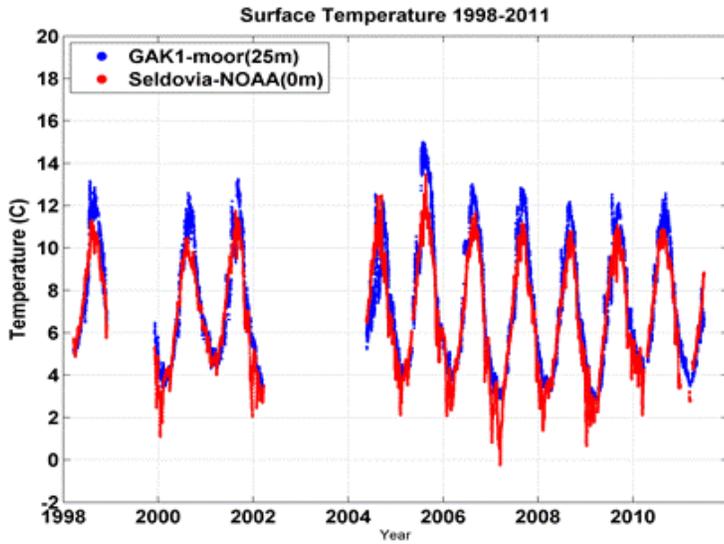


Figure 2-18. Top: Comparison of time series of water temperature (1998-2011) from GAK 1 mooring (25 m depth, blue) and Seldovia tide gauge station (near surface, red), with a 2-day running mean. Gaps in the GAK 1 mooring data record are not plotted for either time series. Bottom: The mean monthly temperatures based on the GAK 1 mooring at 25 m depth (1998 – 2011), the GAK 1 CTD measurements at the surface (1995 – 2014), and the Seldovia tide gauge data for the same time periods.

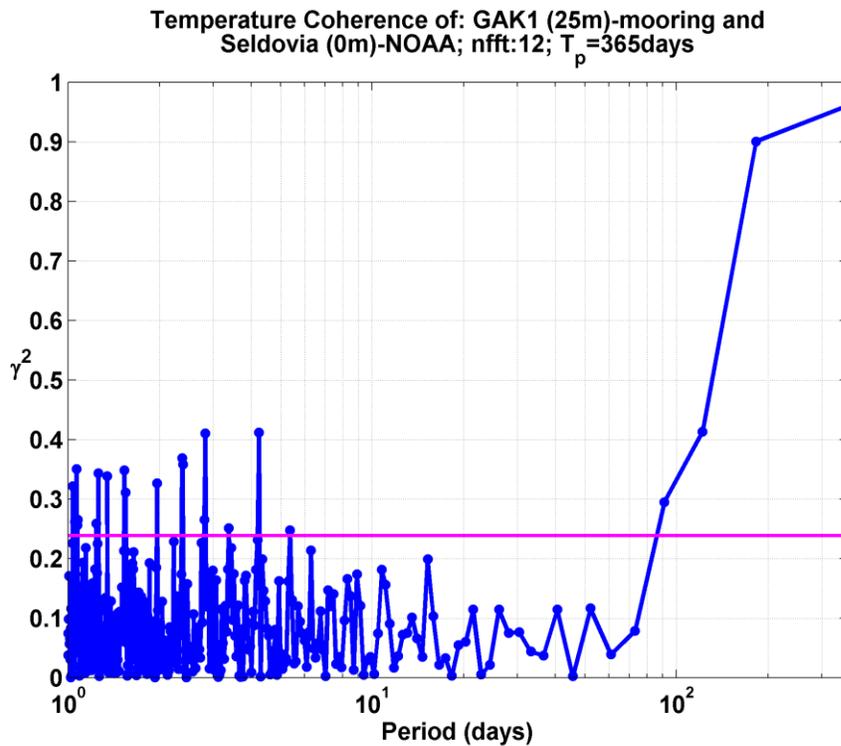


Figure 2-19 Squared coherence as a function of period (days) between temperature at the Seldovia tide gauge (near surface) and the 25 m depth sensor at the GAK 1 mooring. The horizontal line denotes the 95% significance level for coherence squared.

Key Findings and Future Work

The similarity of inner shelf and estuary temperature series at low frequencies has implications for a more synchronous response of the system to inter-annual and basin-scale climate forcing, which is also indicated by the along-shelf tide gauge time series. However, the independence of shelf and estuary temperature data at shorter time periods has significant implications for biological species with shorter life cycles. The variability in ocean conditions at time periods less than three months can drive spatial heterogeneity in primary and secondary production, as well as in forage fish populations. The inherent spatial variability also has implications for the monitoring needs for ocean conditions within the region.

Additional highlights from field work in 2012-2014 include the quantification of rapid changes in oceanographic conditions and plankton across persistent, tidal current and bathymetry-linked fronts and convergence zones in lower Cook Inlet, with implications for the development of biological hotspots. We have also identified consistently strong stratification for more of the year than originally anticipated, except in tidal rip areas, that indicates the importance of buoyancy flux in estuarine waters, as well as on the shelf.

References

- Alaska Ocean Observing System (AOOS), 2005. Shumacher, J.D., ed. Cook Inlet Physical Oceanography Workshop Proceedings. 106 pp.
- Kachemak Bay Research Reserve (KBNERR) 2010. System-Wide Monitoring Program: Summary Report 2001-2010.
- Mantua, N.J. and S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78, pp. 1069-1079.
- Muench, R.D., H.O. Mofjeld, and R.L. Charnell. 1978. Oceanographic conditions in Lower Cook Inlet: spring and summer 1973. *J. Geophys. Res.*, 83(C10): 5090–5098.
- Okkonen, S.R. and S.S. Howell. 2003. Measurements of temperature, salinity and circulation in Cook Inlet, Alaska. OCS Study MMS 2003-036: 32 pp.
- Okkonen, S.R., S. Saupe, and W.S. Pegau. 2009. Seasonality of Boundary Conditions for Cook Inlet, Alaska. OCS Study MMS 2009-041: 60 pp.
- Spies, R. B., editor. 2006. Long-term ecological changes in the northern Gulf of Alaska, 1st edition. Elsevier Science.
- U.S. Coast and Geodetic Survey (C&GS), 1961. Surface water temperature and salinity. Pacific Coast, North and South America and Pacific Ocean Islands. C&GS pub. 31-3.

RESEARCH SUMMARY: INTERANNUAL VARIABILITY IN LOWER TROPHIC LEVELS ON THE ALASKAN SHELF

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Extended Abstract

The south Alaskan Shelf region that encompasses the large inlets of Cook Inlet (CI) and Prince William Sound (PWS) and the outer shelf of the northern Gulf of Alaska is a productive, dynamic, subarctic shelf system supporting numerous valued marine resources such as commercially-harvestable fish (e.g. herring, salmon, groundfish), large marine mammals (e.g. belugas, hump-backed whales), and seabirds. Lower trophic level productivity underpins this ecosystem but our understanding of plankton variability in this region is still somewhat limited. With short generation times, limited mobility and lack of a commercial harvest, plankton often respond to changes in their environment more rapidly and less ambiguously than higher trophic levels, so that a decadal-long time series of plankton can provide insights into the responses of the shelf ecosystem to some of the processes described previously in this document. Primary productivity is strongly seasonal in this region, owing primarily to the relatively high latitude and low light levels in winter. Previous studies of zooplankton on the shelf (Coyle and Alexei 2003) and in PWS (Cooney et al. 2001) suggest a strongly seasonal community dominated by copepods (with significant contributions from other taxa such as cnidarians on the shelf, euphausiids, pteropods and larvaceans seasonally in PWS). Negative salinity anomalies, followed by temperature, were the strongest influencers of the zooplankton community (Coyle and Pinchuk 2003). The study described here reports results from the first 13 years of the Continuous Plankton Recorder (CPR) program that has sampled the lower trophic levels (restricted to larger, hard-shelled phytoplankton and robust zooplankton taxa). Sampling took place along a transect from the open ocean across the shelf (into CI from 2004 to 2012, Figure 2-3 and to the entrance to PWS from 2000 to 2003) to provide plankton abundance data, at monthly intervals from spring through autumn of each year.

Although the CPR was not designed as a phytoplankton sampler, and the mesh size is larger than many phytoplankton cells, there are nonetheless valuable insights into phytoplankton variability that can be gained from CPR data, because it is an internally consistent sampler and does retain a representative proportion of even quite small cells (especially if chain-forming). This study demonstrates that seasonal cycles derived from the CPR data closely replicate those seen from satellites for the same area, confirming that useful information can be gained (Figure 2-20). Through the time series of CPR sampling on the Alaskan Shelf we have found that warm years had generally higher abundances of the larger cells retained by the CPR, particularly of diatoms. The diatom anomaly time series (Figure 2-21) has some similarity to a chlorophyll *a* anomaly time series derived from satellite measurements of chlorophyll-*a* for a wider area of the coastal Gulf of Alaska (Waite and Mueter 2013). Their time series showed positive anomalies from 1998 to 2002, negative anomalies from 2003 to 2005, close to average for 2006 to 2010, and strongly negative in 2011. The CPR diatom anomalies were high in the early years also, suggesting a

widespread event, and the decline in the middle years was probably not related to the change in time series location since the Waite and Mueter study showed a similar decline in chlorophyll-*a* at this time. The strongly negative anomaly in 2011 was common to both time series, and also noted by researchers in the North Pacific Research Board's Gulf of Alaska Integrated Ecosystem Research program (GOAIERP) with a field year in 2011 (Strom 2013). Causes of the low productivity year are still being explored, however, the CPR zooplankton data show that the effects passed up the food chain from the phytoplankton; zooplankton biomass had the lowest anomaly of the time series to date in 2011.

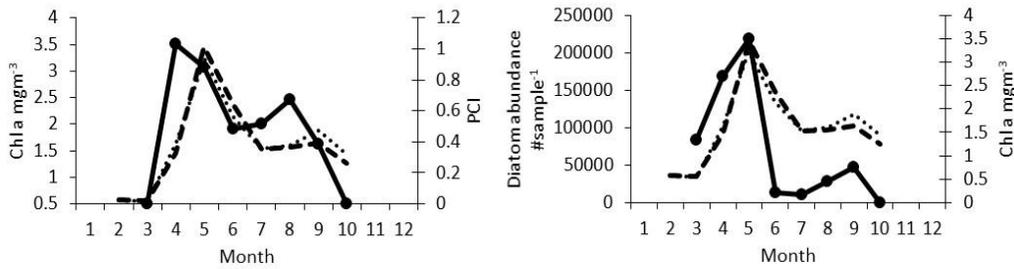


Figure 2-20. Mean monthly phytoplankton indices from CPR data (solid line, Phytoplankton Color Index at left, diatom abundance at right) and satellite-derived chlorophyll *a* (from MODIS, heavy dashed line and SeaWiFS, lighter dashed line on both graphs) for the region shown in Figure 1, excluding Cook Inlet.

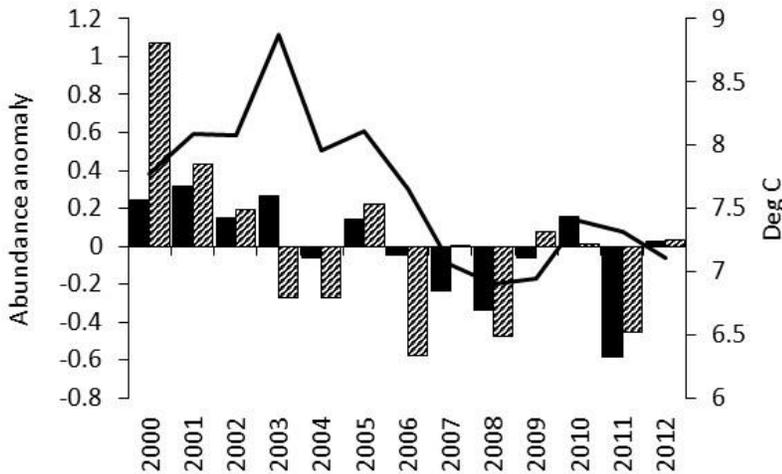


Figure 2-21. Annual abundance anomalies for diatoms (solid bars) and dinoflagellates (shaded bars) together with mean annual SST (line). See methods for derivation of these variables.

Diatom spring phenology (timing) revealed an influence by water column conditions (Figure 2-22). Although the Seward line May thermocline depth did not show a relationship with diatom spring

phenology, this is the time of year when the thermocline is just beginning to be set up and it has high variability in May along the line. However, the salinity, which is also important in setting up water column stability, did show a significant correlation and years with lower salinity, therefore a stronger density gradient, had an earlier peak. There was also a strong correlation with the North Pacific Gyre Oscillation (NPGO) index, which is known to explain salinity variability further south in the California Current system (Di Lorenzo et al. 2008). The NPGO reflects both regional and basin scale variations in wind-driven circulation and advection processes. The significant correlation with the diatom timing emphasizes that phytoplankton processes are very much dependent on the oceanographic conditions.

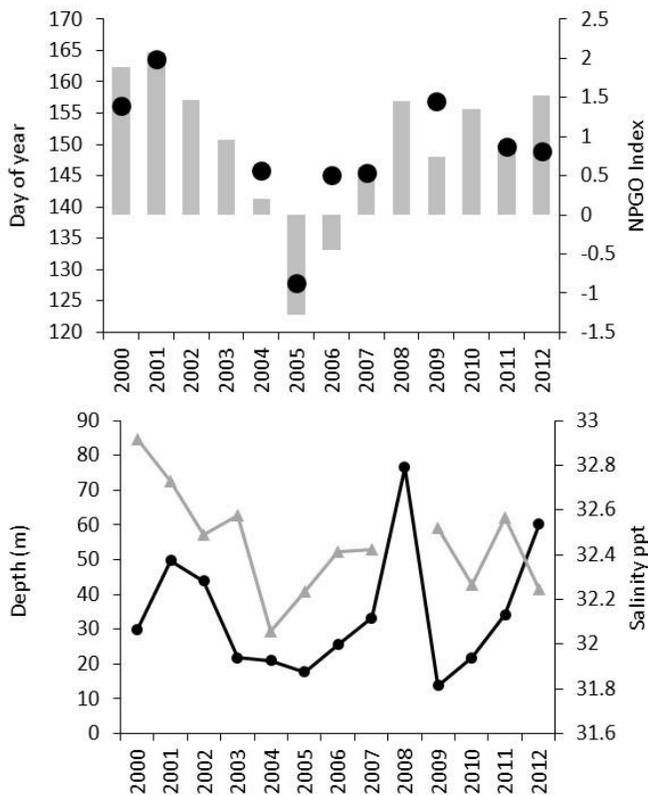


Figure 2-22. Top panel an estimate of peak diatom abundance timing (points) as day of year and mean annual NPGO index (bars). Lower panel; May thermocline depth along the Seward Line (mean of all stations) in black and mean May surface salinity (outer Seward line stations) in grey.

Total mesozooplankton biomass was shown to be positively correlated with diatom abundance, and less strongly but still positively, the abundance of major zooplankton groups. These CPR data thus support the hypothesis that the physical environment of the Gulf of Alaska shelf (in this case SST and salinity) influences the phytoplankton (diatom abundance and phenology), which in turn controls the quantity of mesozooplankton. We can therefore speculate that higher trophic levels such as fish will be influenced.

Copepod seasonal timing is also dependent on temperature (Figure 2-23), since copepods are cold-blooded and their metabolic processes, including development rate, are faster in warm conditions (Batten et al. 2003, Mackas et al. 2007). The index of season mid-point calculated here ranged from day 125 to day 200 for large copepods, and day 154 to day 232 for small copepods (and for both size classes is earlier in warmer years and later in colder years). This is a considerable amount of variability – over 2 months in each case, and could potentially impact larger predators that time their reproduction or migration to take advantage of a peak in their prey. Zooplankton community composition was also influenced by temperature with changes not as dramatic as a replacement of many species by others, but rather a change in relative abundances with temporary occurrences of some rare species (*e.g.*, the copepod *Acartia danae*, usually found south of 40°N but found in the CPR samples from the Alaskan shelf in the warm year 2005). CPR data from the oceanic NE Pacific have noted the northwards extension of warm water species to the GOA in the warmest years of the last decade, and other researchers report a seasonal invasion of southern species along the Seward Line also in the warm year 2005 (Hopcroft et al. 2007, Batten and Walne 2011). If warm water species contribute a significant amount to the zooplankton populations, they could present a dietary challenge to zooplankton predators assuming their nutritional quality varies from the more typical subarctic diet.

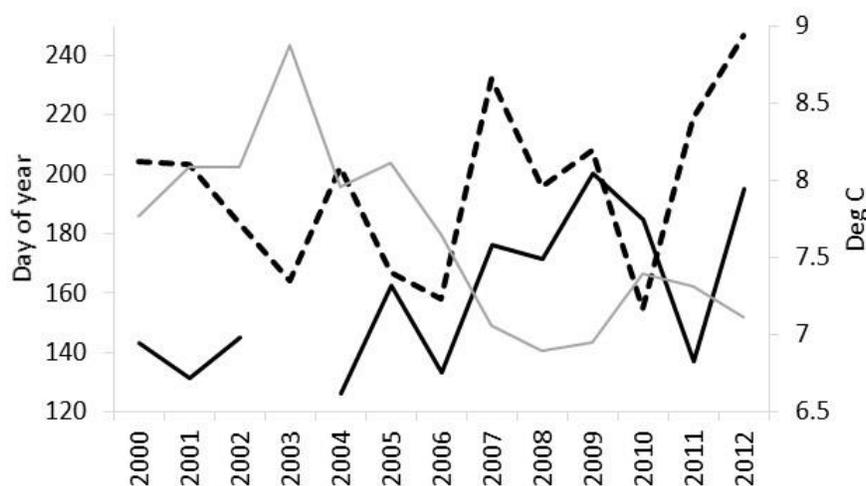


Figure 2-23. Day of year when 50% of the cumulative annual abundance of copepods was reached. Large Copepods = solid black line, Small Copepods = dashed black line. Mean annual SST is also shown as the narrow grey line.

In summary then, this manuscript documents interannual variability in concentration and composition of the plankton community of the region over a 13 year time period. At least in part, this can be attributed to changes in the physical environment, particularly salinity and temperature, as they are mediated by large-scale oceanographic processes that can be indexed by the Pacific Decadal Oscillation and NPGO. Our analyses have treated the shelf as one water body, which is an over-simplification since influences of the various current systems which run along the shelf will likely be different on the inner versus the outer shelf. While the large scale resolution of CPR sampling is some mitigation for this approach, we recognize the need to account for across-shelf structure in future analyses.

Literature Cited

- Batten, S. ., R. Clark, J. Flinkman, G. Hays, E. John, a. W. . John, T. Jonas, J. . Lindley, D. . Stevens, and a Walne. 2003. CPR sampling: the technical background, materials and methods, consistency and comparability. *Progress in Oceanography* 58(2-4):193–215.
- Batten, S. D., and a. W. Walne. 2011. Variability in northwards extension of warm water copepods in the NE Pacific. *Journal of Plankton Research* 33(11):1643–1653.
- Cooney, T., K. O. Coyle, E. Stockmar, and C. Stark. 2001. Seasonality in surface-layer net zooplankton communities in Prince William Sound , Alaska. *Fisheries Oceanography* 10(Suppl. 1):97–109.
- Coyle, K. O., and I. Alexei. 2003. Annual cycle of zooplankton abundance , biomass and production on the northern Gulf of Alaska shelf , October 1997 through October 2000. *Fisheries Oceanography* 4/5(2003):327–338.
- Hopcroft, R., K. O. Coyle, T. Weingartner, and T. Whiteledge. 2007. *Gulf of Alaska Long-term Observations: the Seward Line*. Anchorage, AK.
- Di Lorenzo, E., N. Schneider, K. M. Cobb, P. J. S. Franks, K. Chhak, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchitser, T. M. Powell, and P. Rivière. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* 35(8):L08607.
- Mackas, D. L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. *Progress in Oceanography* 75(2):223–252.
- Strom, S. 2013. *Phytoplankton communities and processes in the coastal Gulf of Alaska: implications of an anomalous year*. Anchorage, AK.
- Waite, J., and F. J. Mueter. 2013. Spatial and temporal variability of chlorophyll-a concentrations in the coastal Gulf of Alaska, 1998–2011, using cloud-free reconstructions of SeaWiFS and MODIS-Aqua data. *Progress in Oceanography* 116:179–192.

RESEARCH SUMMARY: HYDROGRAPHIC TRENDS IN PRINCE WILLIAM SOUND, ALASKA, 1960-2013.

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Introduction

The surface waters of the continental shelf adjacent to Prince William Sound (PWS) is dominated by the relatively fresh Alaska Coastal Current and the Copper River, which is the largest point source of fresh water to the northern Gulf of Alaska (Stabeno et al. 2004). PWS is connected to the coastal Gulf of Alaska through two main entrances, Hinchinbrook Entrance (HE) and Montague Strait (MS), with surface waters generally entering through HE and exiting through MS, although reflux events do occur. Deepwater renewal events generally occur through HE in summer and autumn (Halverson et al. 2013). The surface waters of PWS also receive freshwater from numerous streams, small rivers, and ice fields along the periphery, as well as considerable sediment loading (Feely et al. 1979, Gay and Vaughan 2001). Precipitation in the region is prodigious, with order of 95 km^3 of fresh water moving through the system each year, which accounts for 11% of all freshwater discharge of the Gulf of Alaska (Neal et al. 2010).

Warming trends have been observed globally for many years (Levitus et al. 2001), and those trends have also been observed in Alaska (Shulski and Wendler 2008). Much of the increased heat flux has been taken up by the ocean (Barnett et al. 2005), and warming trends have been observed in coastal Alaska at the regularly sampled GAK line near Seward, Alaska (Royer and Grosch 2006). Furthermore, much of the margin of the Gulf of Alaska is covered by glaciers and ice sheets, and those ice resources have been losing mass in recent decades (Wiles et al. 1999, Barclay et al. 2013), at rates that are among the highest in the world (Gardner et al. 2013). Precipitation rates have also been increasing over time (Stafford et al. 2000, Royer and Grosch 2006).

Although there is a well-maintained time-series of the coastal Gulf of Alaska in the GAK line, there has not been a comparable coordinated long-term sampling effort in Prince William Sound. Prior to the 1989 *Exxon Valdez* Oil Spill, oceanographic observations were sparse and scattered. Following the spill, there were a number of large field campaigns, including the SEA (1992-1998), GLOBEC (1997-2004) and PWS Herring Survey/Gulf Watch Alaska projects (2009-present). However, sampling by those projects was also episodic, and in many cases visited different stations in different parts of PWS at different times. Given the trends observed elsewhere, it can be expected that there have been changes in the PWS region as well. It is therefore the goal of this study to assemble the many hydrographic (temperature and salinity) observations that have been made in the PWS region to produce a time series of observations to describe how the hydrography of the region has changed.

Methods

Profiles of temperature and salinity were collected from several sources. The database described by Musgrave et al. (2013) was used, which includes casts taken between 1973-2010 by several coordinated projects and various methods (STD, CTD, XCTD, XBT), which was merged with casts from the NOAA NODC World Ocean Database. Casts in the database were verified with automated methods to eliminate duplicate casts, and for physically unlikely values ($-2^\circ\text{C} < T < 25^\circ\text{C}$, $0 < S < 35$), and questionable casts were visually examined prior to being discarded.

In addition, casts done as part of recent oceanographic monitoring programs supported by Gulf Watch Alaska were included. Those data were collected from 2009 to present at 12 standard stations in the PWS region with a Seabird Electronics SBE 9, SBE19 or SBE25 CTD. For analysis, the casts were grouped into four areas corresponding to the Gulf of Alaska (GOA), central Sound (CS), east (E) and northwest (NW) regions defined by Musgrave et al. (2013; **Error! Reference source not found.**). There were 1721, 3117, 456 and 3951 individual casts within the GOA, CS, E and NW domains, respectively.

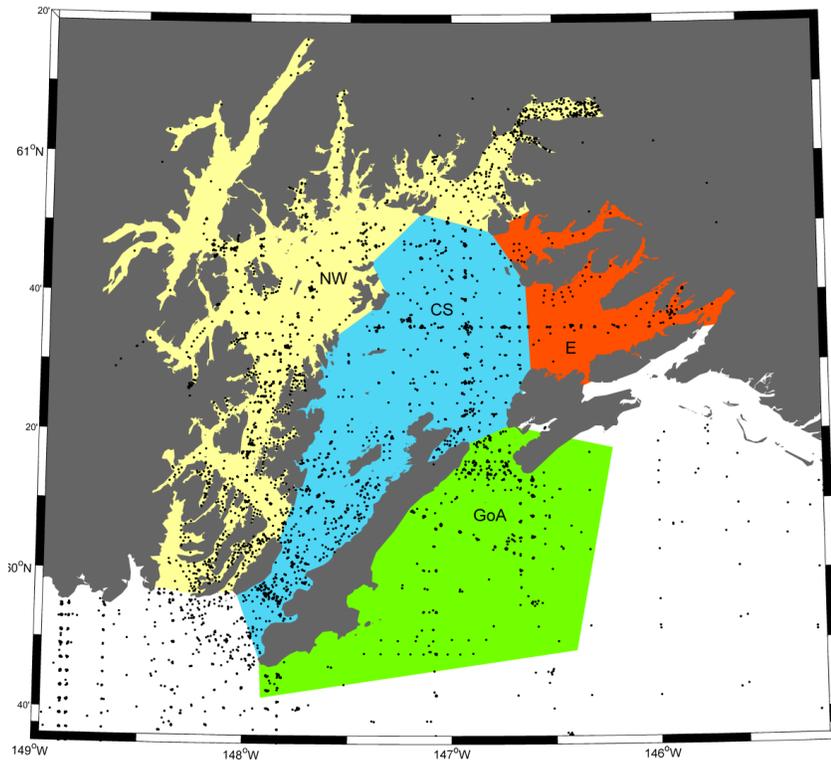


Figure 2-24. Position of CTD casts in the CTD database used in this study, and geographic regions assigned to the casts (E=eastern PWS; NW=northwest PWS; CS=central PWS; GOA=Gulf of Alaska). See Musgrave et al. (2013) for a discussion of the choice of regions.

It is at the surface that changes in atmospheric and freshwater forcing are most likely to occur, and in the case of temperature, there is a network of surface observations (from buoys and ships of opportunity) that are generally at much higher frequency than cast data. For this study, sea surface temperature (SST) from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS:(NOAA 2014) were used. SST data were sparse in the PWS region prior to 1960, and data prior to January 1st of that year were not used. The SST data were also assigned to the four spatial domains (see Figure 2-24), there were approximately 161,000, 122,000, 1,000 and 81,000 individual observations in the GOA, CS, E and NW domains, respectively.

The data used in this study presented a number of analytical challenges, caused by the spatial and temporal heterogeneity of the samples (as is to be expected with archived data). Breaking the observations out into spatial domains attempts to remove the effect of spatial heterogeneity in the dataset by combining stations that can be expected to be similar (a discussion of the choice of the regions is given by Musgrave et al. (2013)). The observations in the dataset were also temporally scattered, creating a challenge for standard time series and frequency domain methods that require a regularly sampled time series. All regressions done in this study were done by nonlinear least squares using a Trust Region Reflective algorithm (Branch et al. 1999), with a termination tolerance of 10^{-6} . Depth specific fits to the entire dataset showed that a second order cosine curve tended to describe the seasonal cycle in temperature and salinity reasonably well (Campbell, in prep.), allowing reconstruction of climatological annual cycles (Figure 2-25 and Figure 2-26) for each domain. The cosine curve was of the following form:

$$H_z(t) = \bar{y} + \sum_{k=1}^2 C_k \cos \left[\frac{2\pi kt}{365} - \varphi_k \right]$$

Where H is the hydrographic quantity of interest (temperature or salinity, for a specific depth, z), t is the day of the year (i.e. a number between 1 and 365.25). The constant, \bar{y} , may be thought of as the seasonally detrended average, while C_k and φ_k describe the amplitude and phase respectively of the components. Equation 1 was also extended to a simple regression model incorporating a long-term slope (β_1) that was fit through the entire dataset in each depth bin.

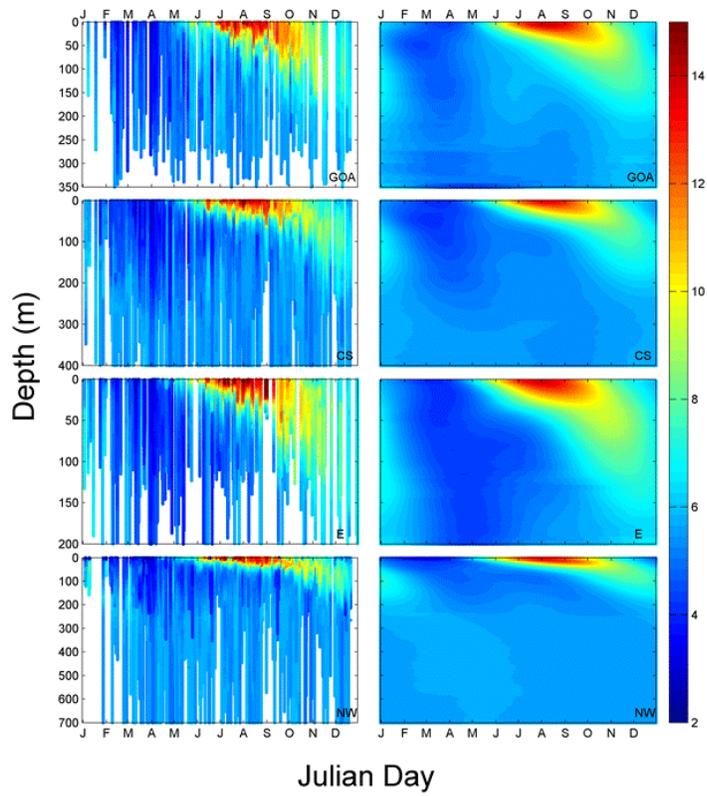


Figure 2-25. Annual temperature cycle by geographic regions (top to bottom: GOA, CS, E, and NW). Left panels present the actual data from the 1-m binned CTD database (i.e. all years are compressed into a single composite year), and right panels are the model fits.

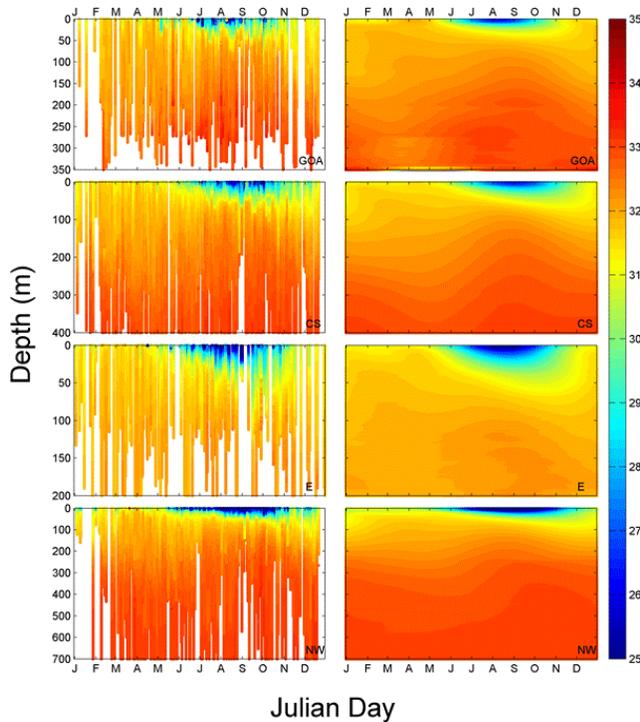


Figure 2-26 Annual salinity cycle by geographic regions (top to bottom: GOA, CS, E, and NW). Left panels present the actual data from the 1-m binned CTD database (i.e. all years are compressed into a single composite year), and right panels are the model fits.

To detect long-term trends in SST, following Royer (1993) the SST time series was filtered with a lowpass second order Butterworth filter with a 5 year cutoff. Prior to filtering the time series was interpolated onto a regular daily time series by linear interpolation. As well as long-term trends that can be expected to follow as a result of global and basin scale changes, it has been shown that air and sea surface temperatures respond to low frequency changes in tidal mixing set up by the 18.6 year lunar declination cycle (Loder and Garrett 1978, Royer 1993). As well as linear fits to the parameters, the progression of the 18.6 year nodal tide was estimated with the negative of the longitude of the Moon's ascending node, N' (Dodson, 1921).

Results

The slope of the simple regression model applied to the cast data in each 1 m depth bin indicated a significant warming trend in the GOA region at all depths, and a warming trend at depth in central PWS and the NW region (**Error! Reference source not found.**). Most of the slopes in the E region had confidence intervals that span zero, and thus were not significant (the E region had the smallest number of casts and the poorest temporal coverage). There was also a significant cooling trend in the NW region between 3 and 23 m (negative slopes also occurred in the CS region, but confidence intervals spanned

zero). There was a trend towards increased salinity at depth in the GOA and CS regions, and at mid depths (approximately 100–250m) in the NW region (**Error! Reference source not found.**).

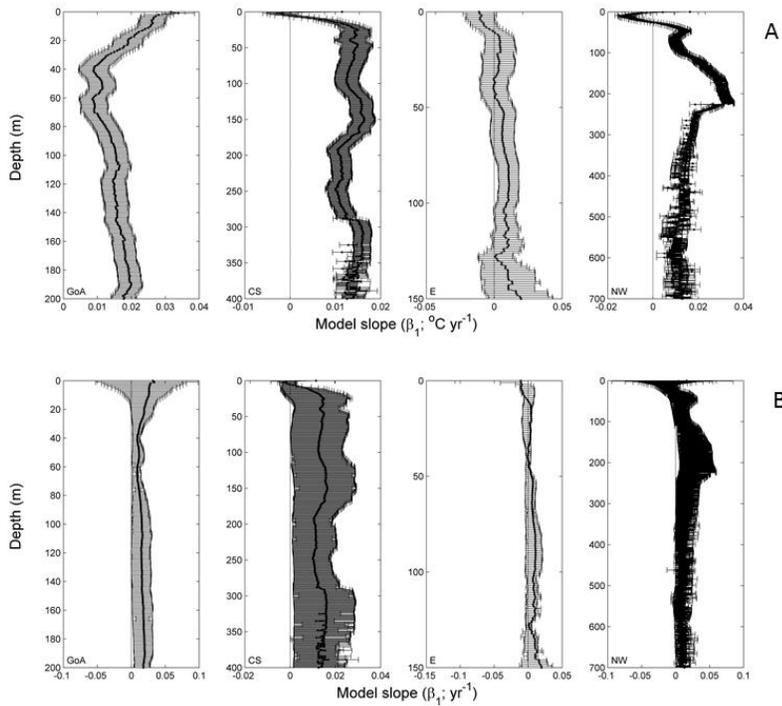


Figure 2-27 Profiles of β_1 (i.e. the long-term slope in eq. 2) in temperature (A) and salinity (B), in the four geographic regions (from left to right: GOA, CS, E and NW). Error bars indicate 95% confidence intervals for the parameter. Note that both axes change among figures.

The trends in the parameters from the annual model fits returned similar results with significant trends in the \bar{y} term indicating a warming trend at depth in the GOA region, and over most depths in the CS region (Figure 2-28, left panel); there were few significant trends in salinity: a minor freshening in the NW region and a trend towards higher salinity at depth in the GOA and central PWS. The annual amplitude component (C_1) had a significant positive trend in the near surface in the NW region, and a negative trend at depth (Figure 2-28, left panel), and a significant negative trend in salinity at the surface in the GOA region (Figure 2-28, right panel). There were few significant trends in the phase term (ϕ_1) for temperature, with a positive trend in the GOA region at depths $> 250\text{m}$ (Figure 2-28, left panels). For salinity, there was a negative trend at the surface in the GOA region, and a positive trend near surface in the NW region (Figure 2-28, right panel).

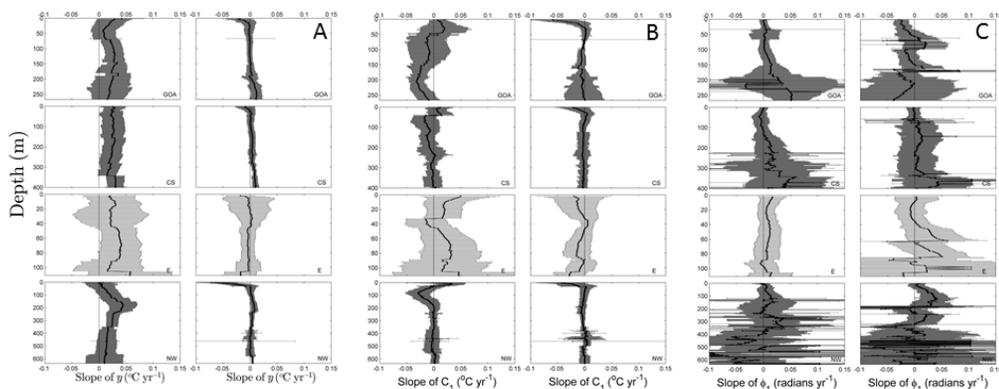


Figure 2-28 Profiles of the slope of y (A), C_1 (B), ϕ_1 (C), and over time in the four geographic regions for temperature (left panel) and salinity (right panel). Bars indicate 95% confidence intervals. Note that the scaling of the ordinate differs among region

Filtered SST was loosely aligned with N° (Figure 2-29), with a number of peaks out of phase. Filtered SST correlated best with N° with a lag of 2 years within PWS and a lag of 3 years in the GOA region (Figure 2-29). The strongest correlation was in the Eastern PWS, with weaker correlations in the other regions (explaining approximately 20-30% of the variance). All correlations were significant with $p < 0.05$.

Analysis of the SST observations on an annual basis also showed a warming trend in the GOA region (positive slope of \bar{y} : Figure 2-30), and minor cooling trends in the other regions, which were not significantly different from zero. There were negative trends in the C_1 parameter in all regions, (Figure 2-30) but it was significantly different from zero in only the CS region. There were also negative trends in the ϕ_1 parameter that were significantly different from zero in the GOA and NW regions (Figure 2-30).

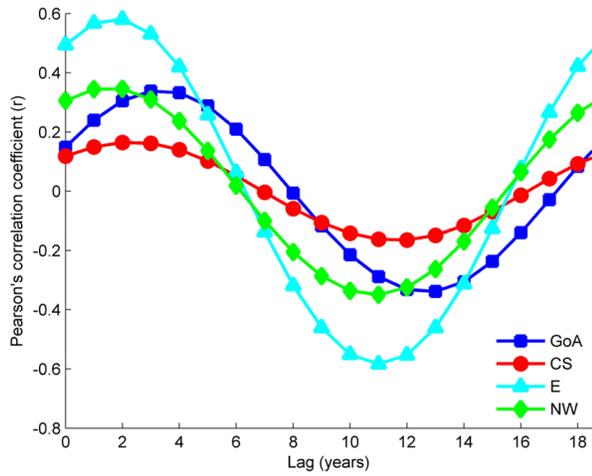


Figure 2-29. Lag correlations between filtered SST and N' in each geographic region. All correlations were significant with $p < 0.05$.

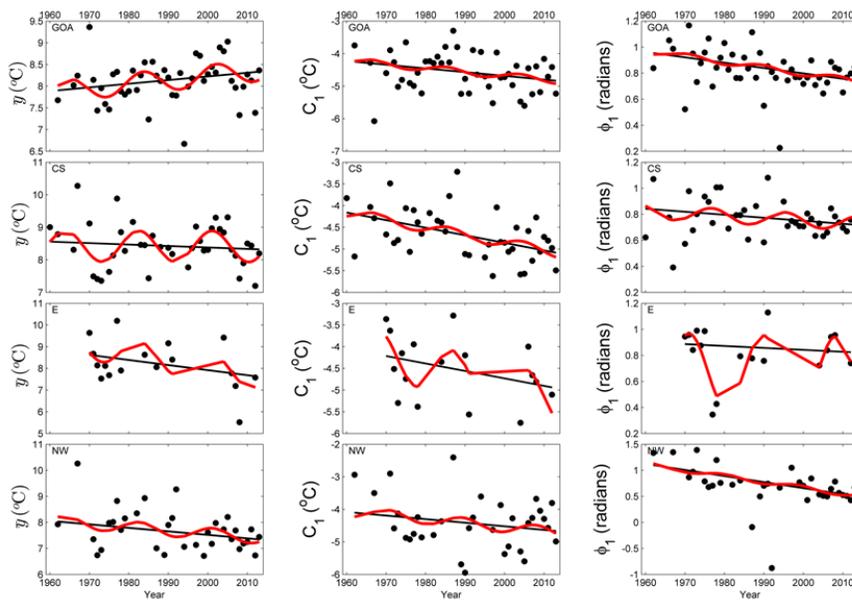


Figure 2-30. Time series of \bar{y} (A) and C_1 (B), and ϕ_1 (C), including annual fits of SST to eq. 1. The red line indicates the fit of the full regression model including the 18.6 year component, and the black line is the fit to the linear trend portion (β_0 and β_1).

Discussion

The magnitude of the trends observed by this study were much less than the considerable inter- and intra-annual variability in temperature and salinity. There is no doubt considerable high frequency temporal and spatial variability: Vaughan et al. (2001) highlight the spatial and temporal variability in temperature and salinity in central PWS that is caused by smaller scale oceanographic processes (and all the data used by Vaughn et al. (2001) is included in this study). This type of analysis cannot account for that high frequency variability, and it is assumed that considerable variability surrounds the mean. Most prior work in the north Pacific has been from a small number of regularly visited stations (Royer 1993, Royer et al. 2001, Royer and Grosch 2006), but there has not been a similar coordinated effort undertaken in the PWS region. It can be expected that using ensembles of stations in this way will increase the likelihood of type II errors and will likely therefore fail to detect some existing patterns. For this reason a number of complimentary methods and models were used, but they did not always agree which leads to some ambiguities in the interpretations.

The climatological annual cycle that emerges from this analysis is similar from region to region and similar to that of Xiong and Royer (1984): following winter minima in February-April, surface temperatures begin to warm in May, with warming largely confined to the upper 25 m of the water column (fig. 2-27). The pycnocline is mixed down into the water column as stability breaks down. The salinity cycle is similar, with surface salinity decreasing in late May, decreasing over the summer, and being mixed downward in autumn (Figure 2-25). Salinity also tends to increase at depth during the summer months (June-Sept), as deepwater renewal occurs. Halverson et al. (2012) observed using moorings annual deepwater renewal events through Hinchinbrook Entrance between 2005 and 2010.

In the waters adjacent to PWS (the GOA region), there was a warming trend in the last 30 years of approximately 0.2-0.3°C per decade, with most warming at the surface (Figures 2-26,2-27), as has been observed as part of a larger pattern of warming throughout the region (Royer and Grosch 2006, Wu and Li 2007). Beyond an overall increase in temperature, the annual model fits did not suggest any meaningful changes in the magnitude of the annual peak or in timing.

At depth (>150 m), there was an indication of an overall decrease in the amplitude of the annual temperature peak (Figure 2-27), and a shift towards later timing. The freshening trend observed by Royer and Grosch (2006) at a site off Seward, AK was less evident in the GOA region, with some indication of freshening at the surface from the annual analysis of casts (marginally significant at the near surface: fig. 2-27), but a trend towards higher salinities at depth. These observations suggest an enhancement in deep water renewal events over time, with more high salinity water transported in during the deep water renewal season. An enhancement in deep water renewal could also be expected to accompany decreases in surface salinity as enhanced surface currents will cause entrainment of more saline water at depth (Royer, 2005).

In central PWS there was also a warming trend of similar magnitude to GOA at most depths identified by both the simple and annual regression models, there was again no suggestion of changes in timing or magnitude of the summer peak. Analysis of the SST data was ambiguous: the regression model suggested an increase over time, but analysis on an annual basis showed a significant decline in \bar{y} , as well as a significant 18.6 year component. Trends in salinity were similar to that of the GOA region as well, with an increase at depth and non-significant increase at the surface. The interpretation for those trends is

essentially the same as the GOA region: PWS may be considered to be a large estuary, and enhanced freshwater fluxes at the surface can be expected to increase entrainment and bring in more saline water at depth. The eastern portion of PWS also showed the same trends, although they were less likely to be detectable, presumably due to the comparatively lower data density there (rather than combining the region with CS, it has been left separate to preserve the regions used by Musgrave et al. 2013).

In Northwestern PWS there were some ambiguities between the different models: the simple regression model showed declining temperatures near surface and a warming trend at depth; annual regressions did not show a reduction in annual mean temperature (\bar{y}) near surface, but did show a negative trend in the peak temperature parameter (C_1 ; Figure 2-27). Annual regressions (which are more restrictive, since years with few observations are dropped) found a non-significant negative trend in \bar{y} . There was a significant warming trend in \bar{y} at deeper depths, corresponding to the depths where a warming trend was also identified in the CS region. In salinity, there was a trend towards declining salinity at the surface, but no significant trend at depth. The overall picture suggests a cooling and freshening at the surface, and a warming and increasing salinity trend at depth. The northwestern portion of PWS is bounded on the west by the Sargent Icefield of the Kenai Peninsula, and to the north by the many glaciers of the Chugach mountains, and the surface salinity and temperature trends likely reflect a signal from the melting and recession of those glaciers. As before, entrainment is the likely mechanism for increases in salinity at depth.

There was an 18.6 year cycle evident in the SST record (Figure 2-28), but not in the cast data, likely at least in part because the SST record had much better spatial and longer temporal coverage. An 18.6 year periodicity is a common feature of geophysical time series of adequate length (Curry, 1996). The mechanisms by which the lunar declination cycle alter surface temperature are unclear, it has been hypothesized that changes in tidal mixing or ocean-atmosphere heat flux. McKinnell and Crawford (2007), working with SST data from British Columbia noted a two year lag correlation between the lunar nodal cycle signal and the Pacific North America teleconnection index, which is an indicator of low frequency variability in atmospheric circulation in the north Pacific (Barnston and Levezey 1987), indicating that the effect is likely part of much larger circulation patterns in the hemisphere. The lag observed here was of similar magnitude (2-3 years).

The overall picture that emerges from the data assembled here is in line with a regional warming trend, with some indications of enhanced freshwater inputs at the surface that are sometimes accompanied by a reduction in temperature that can be attributed to inputs from melting ice. At depth, the trend is towards warmer and more saline water, which is consistent with increased entrainment of deep water caused by enhanced surface circulation, again due to increasing freshwater inputs.

Literature cited

- Barclay, D. J., E. M. Yager, J. Graves, M. Kloczko, and P. E. Calkin. 2013. Late Holocene glacial history of the Copper River Delta, coastal south-central Alaska, and controls on valley glacier fluctuations. *Quaternary Science Reviews* 81:74–89.
- Barnett, T. P., D. W. Pierce, K. M. Achutarao, P. J. Gleckler, B. D. Santer, J. M. Gregory, and W. M. Washington. 2005. Penetration of human-induced warming into the world's oceans. *Science* (New York, N.Y.) 309(5732):284–7.

- Barnston, A., and R. Levezey. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review* 115:1083–1126.
- Branch, M. A., T. F. Coleman, and Y. Li. 1999. A Subspace, Interior, and Conjugate Gradient Method for Large-Scale Bound-Constrained Minimization Problems. *SIAM Journal of Scientific Computing* 21:1–23.
- Feely, R. A., E. T. Baker, J. D. Schumacher, G. J. Massoth, and W. M. Landing. 1979. Processes affecting the distribution and transport of suspended matter in the northeast Gulf of Alaska. *Deep Sea Research* 26(4A):445–464.
- Gardner, A. S., G. Moholdt, J. G. Cogley, B. Wouters, A. a Arendt, J. Wahr, E. Berthier, R. Hock, W. T. Pfeffer, G. Kaser, S. R. M. Ligtenberg, T. Bolch, M. J. Sharp, J. O. Hagen, M. R. van den Broeke, and F. Paul. 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science (New York, N.Y.)* 340(6134):852–7.
- Gay, S. M., and S. L. Vaughan. 2001. Seasonal hydrography and tidal currents of bays and fjords in Prince William Sound, Alaska. *Fisheries Oceanography* 10:159–193.
- Halverson, M. J., C. Bélanger, and S. M. Gay. 2013. Seasonal transport variations in the straits connecting Prince William Sound to the Gulf of Alaska. *Continental Shelf Research* 63:S63–S78.
- Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and a J. Broccoli. 2001. Anthropogenic warming of Earth's climate system. *Science (New York, N.Y.)* 292(5515):267–70.
- Loder, J. W., and C. Garrett. 1978. The 18.6-year cycle of sea surface temperature in shallow seas due to tidal mixing. *Journal of Geophysical Research* 83(C4):1967–1970.
- McKinnell, S. M., and W. R. Crawford. 2007. The 18.6-year lunar nodal cycle and surface temperature variability in the northeast Pacific. *Journal of Geophysical Research* 112(C2):C02002.
- Musgrave, D. L., M. J. Halverson, and W. Scott Pegau. 2013. Seasonal surface circulation, temperature, and salinity in Prince William Sound, Alaska. *Continental Shelf Research* 53(March 1989):20–29.
- Neal, E. G., E. Hood, and K. Smikrud. 2010. Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophysical Research Letters* 37(6):n/a–n/a.
- NOAA. 2014. International Comprehensive Ocean-Atmosphere Data Set. <http://icoads.noaa.gov/>.
- NODC, and NOAA. (n.d.). World Ocean Database. http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html.
- Royer, C. 1993. High-Latitude oceanic variability associated with the 18.6-Year nodal tide 98(C3):4639–4644.
- Royer, T. C. 2005. Hydrographic responses at a coastal site in the northern Gulf of Alaska to seasonal and interannual forcing. *Deep Sea Research Part II: Topical Studies in Oceanography* 52(1-2):267–288.

- Royer, T. C., and C. E. Grosch. 2006. Ocean warming and freshening in the northern Gulf of Alaska. *Geophysical Research Letters* 33(16):L16605.
- Royer, T. C., C. E. Grosch, and L. a Mysak. 2001. Interdecadal variability of Northeast Pacific coastal freshwater and its implications on biological productivity. *Progress in Oceanography* 49(1-4):95–111.
- Shulski, M., and G. Wendler. 2008. *The Climate of Alaska*. University of Alaska.
- Stabeno, P. J., N. A. Bond, A. J. Hermann, N. B. Kachel, C. W. Mordy, and J. E. Overland. 2004. Meteorology and oceanography of the northern Gulf of Alaska. *Continental Shelf Research* 24:859–897.
- Stafford, J. M., G. Wendler, and J. Curtis. 2000. Temperature and precipitation of Alaska: 50 year trend analysis. *Theoretical and Applied Climatology* 67:33–44.
- Vaughan, S. L., C. N. K. Mooers, and S. M. G. A. Y. Iii. 2001. Physical variability in Prince William Sound during the SEA Study (1994 – 98). *Fisheries Oceanography* 10(Suppl. 1):58–80.
- Wang, J., M. Jin, E. V. Patrick, J. R. Allen, D. L. Eslinger, C. N. K. Mooers, and R. T. Cooney. 2001. Numerical simulations of the seasonal circulation patterns and thermohaline structures of Prince William Sound, Alaska. *Fisheries Oceanography* 10:132–148.
- Wiles, G. C., D. J. Barclay, and P. E. Calkin. 1999. Tree-ring-dated “Little Ice Age” histories of maritime glaciers from western Prince William Sound, Alaska. *The Holocene* 9(2):163–173.
- Wilks, D. S. 2011. *Statistical methods in the atmospheric sciences*. Elsevier, Oxford, UK.
- Wu, L., and C. Li. 2007. Warming of the North Pacific Ocean: Local Air–Sea Coupling and Remote Climatic Impacts. *Journal of Climate* 20(11):2581–2601.
- Xiong, Q., and T. C. Royer. 1984. Coastal temperature and salinity in the northern Gulf of Alaska, 1970–1983. *Journal of Geophysical Research* 89(C5):8061.

Chapter 3 VARIABILITY WITHIN PELAGIC ECOSYSTEMS OF PRINCE WILLIAM SOUND

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Introduction to Pelagic Ecosystem Monitoring

In the aftermath of the 1989 *Exxon Valdez* oil spill it was difficult to distinguish between the impacts of the spill and background variability in most populations. The main problem was that long-term baseline data for pelagic species were largely absent. As a result managers struggled to make informed decisions in their assessment of damages and recommendations for recovery. For example, marine birds had not been surveyed since the early 1970s and after the spill it appeared there had been major declines. Ten years after the spill it became widely recognized that there had been a major climatic regime shift that altered the entire marine ecosystem prior to the spill, including seabirds and forage species they normally consumed.

The strategy of the pelagic group is to monitor important pelagic species so that we may detect changes in response to future perturbations (Figure 3-1). Long-term and integrated monitoring will provide the critical information needed by managers in the context of a constantly changing environment.

MONITORING CHANGE IN PELAGIC ECOSYSTEMS

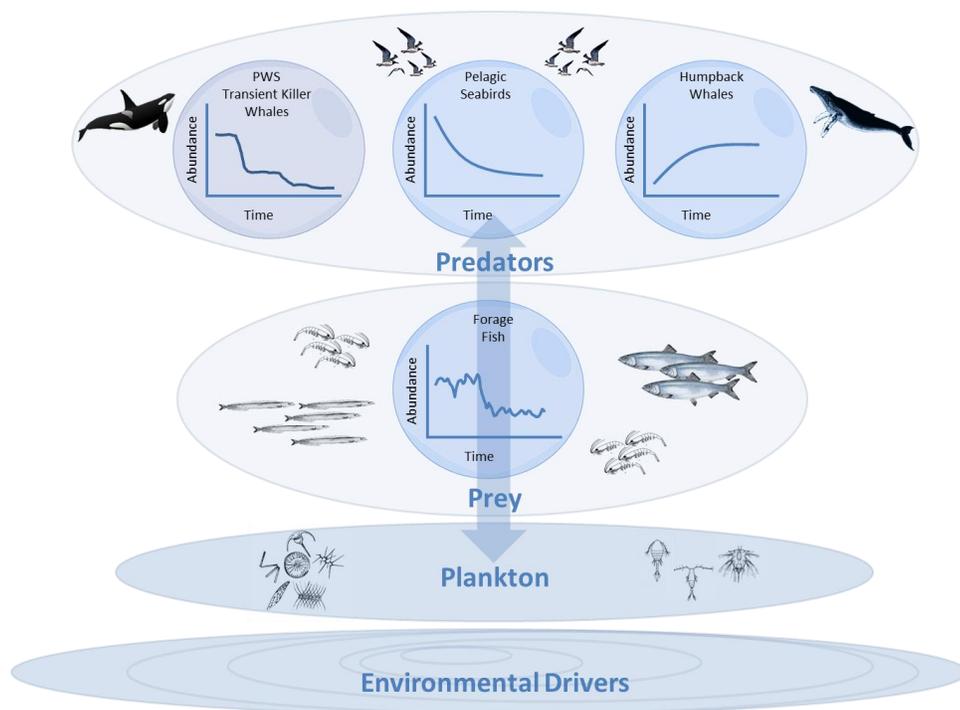


Figure 3-1 A simplified conceptual diagram of the Gulf Watch Alaska pelagic component. Data suggest that key pelagic populations respond differently to perturbations. This model recognizes the potential for top-down control within the system, as well as the more prevalent bottom-up control. The latter is derived from environmental drivers influencing primary and secondary production and thus affecting abundance and availability of middle trophic levels such as euphausiids and forage fish.

This component focuses on species that play a pivotal role in the pelagic ecosystem as trophic indicators for short and long-term ecosystem change: killer whales, humpback whales, forage fish (including euphausiids), and marine birds. The advantage of our approach is that it monitors multiple species that respond in a variety of ways to changes in the environment. For example, the three populations of killer whales in the Northern Gulf of Alaska demonstrated different responses to conditions of the past several decades. One population has declined toward extinction, the second has steadily increased, and a third has maintained a consistent level. Similarly, within the seabird community there have been major declines in pelagic species while several nearshore species have increased over the same time period. In contrast, humpback whales in the North Pacific have made a remarkable recovery since the end of commercial whaling increasing at 5-7% per year. As a large and long-lived species with high energetic demands, humpback whales may be limiting herring recovery in PWS, and thus might also be competing with marine birds for food. Linking these predatory species is a small number of forage species that play a pivotal role in the pelagic food web by transferring energy between plankton and top predators. Unfortunately there is little consistent historic information on forage fish populations.

Pelagic Chapter Articles

This chapter focuses on species that play a pivotal role in the pelagic ecosystem as trophic indicators for short and long-term ecosystem change: killer whales, humpback whales, forage fish, and marine birds. When possible, historic data sets have been assessed with the first three years of Gulf Watch Alaska monitoring data. The chapter includes an introduction, background, and description of the study area and seven separate articles chosen to represent the work from the projects funded under this component within Gulf Watch Alaska. The articles within this chapter are:

- Research Summary: Long-term killer whale monitoring in Prince William Sound/ Kenai Fjords
- Research Summary: Long-term Monitoring of Humpback Whale Predation on Pacific Herring
- Forage Fish Populations in Prince William Sound: Designing Efficient Monitoring Techniques to Detect Change
- Spatial and Temporal Variation in Marine Birds in the Northern Gulf of Alaska: The Value of Marine Bird Monitoring within Gulf Watch Alaska
- Nearshore Marine Bird Surveys: data synthesis, analysis and recommendations for sampling frequency and intensity to detect population trends
- Research Summary: Temporal change in a subarctic marine bird community linked to habitat and climate change
- Research Summary: Long-term monitoring of seabird abundance and habitat associations during late fall and winter in Prince William Sound

Several of the articles are summaries of papers that have been published, submitted, or are in press. In an effort to comply with potential infringement laws, publications have been summarized here, and the citation to the published work provided.

Complexities of Prince William Sound's Pelagic Ecosystem

Pelagic ecosystems of the North Pacific include multiple trophic levels and an array of hundreds of marine species, including many that are critical food for economically important predators (e.g. Pacific herring and salmon). The pelagic ecosystem of Prince William Sound (PWS) is no exception, with species spanning at least five trophic levels (Okey and Wright 2004) and linked in a complex food web. In the context of Gulf Watch Alaska, other chapters have discussed elements strategically linked to pelagic ecosystems detailing conceptual models, characteristics of environmental drivers, and nearshore ecosystems.

In the Gulf of Alaska (GOA), ecosystem models have shown that no single main driver of the ecosystem can explain all species dynamics simultaneously (Gaichas et al. 2011). However in PWS there are some general characteristics that shape the pelagic elements of the ecosystem and the variability therein. Physical processes in PWS include wind, convective currents, temperatures, upwelling, nutrients, and freshwater inputs, and all contribute to high inter-annual variability in productivity (Weingartner 2007). Many of these processes have been shown to be intimately connected to the GOA (Mundy 2005, Spies 2007). This variability in productivity directly affects predator-prey relationships in PWS: resident killer whales prey on salmon that rely on zooplankton and other forage fish including herring (Matkin et al 2014); humpback whales prey on euphausiids (krill) and Pacific herring; and forage fish feed on zooplankton but are also prey for marine birds (Bishop et al. 2015; summary in this document), larger fish (Bishop and Powers 2013), and marine mammals. These bottom-up and top-down trophic relationships

work in concert with each other and rely on critical timing, duration, and density of aggregating forage species for success (Spies and Cooney 2007). Population changes in any one of the pelagic species can lead to trophic cascades throughout the food web (Heithaus et al. 2008) which can result in catastrophic shifts in community structure (Fauchald 2010).

Event driven variability - PWS was generally thought of as a stable and productive environment until the *Exxon Valdez* oil spill in 1989 (EVOS). Unexpected results of the spill were persistence of oil, chronic exposure to oil for certain species, and cascades of indirect effects at the population level (Peterson et al. 2003a). Due to the lack of pre-spill baseline data, the spill provided a unique opportunity for researchers to learn about various species, understand the mechanisms of their injury, and in some cases follow their long-term road to recovery (e.g. sea otters) (Ballachey et al. 2014). Injury from the spill had significant effects on pelagic populations in PWS as well. An extreme result of the spill may be the unprecedented extinction of a unique apex predator population, the AT1 killer whales (Matkin et al. 2012a), with unknown cascading effects at lesser trophic levels. The collapse of the Pacific herring population in PWS has been ascribed to the oil spill (Thorne and Thomas 2007), but this conclusion has been hotly debated (Pearson et al. 2011). At least one marine bird, the pigeon guillemot, was heavily impacted by the spill (Golet et al. 2002) and its population in PWS has yet to recover (Cushing et al., this report). The signs of recovery for many impacted species have been obscured by other forces in the ecosystem (e.g. natural long-term cycles affecting marine bird and forage fish population trends) masking a full understanding of the ecosystem level effects. Because of a lack of pre-spill monitoring, in many cases these effects could not be separated from those of the spill. Tracking effects from the EVOS will be become more difficult as we move further away in time from the initial event.

Regime-driven variability – Natural cycles in the ecosystem can affect pelagic population trends. We recognize that multiple large-scale drivers and forces are capable of causing long-term ecosystem change in PWS. Decadal scale data have increased our awareness and understanding of drivers such as the Pacific Decadal Oscillation (PDO), El Niño/Southern Oscillation (ENSO), and North Pacific Gyre Oscillation (NPGO) (Hollowed et al. 2001b), and we are just starting to consider their relations to pelagic populations in PWS. Additional forces with even greater unknowns are those associated with impending climate change (e.g. warming waters and ocean acidification, see Chapter 1, Figure 1-1. Without monitoring of pelagic species, there will be no chance to isolate and determine effects of these changes.

Monitoring change - Understanding how short and long-term changes affect pelagic populations in PWS requires a multi-pronged approach. First and foremost, long-term population level data sets are an essential foundation for ecosystem monitoring. Second, further development of conceptual and numerical sub-models centered on pelagic ecosystems (top-down control with humpback whale and marine bird predation, bottom-up with environmental forcing on plankton, with forage fish abundance the ecological linchpin) will be an important tool for understanding long-term changes. Over-arching hypotheses such as match-mismatch, physiological performance-temperature mediated survival, and on-shelf/off-shelf productivity will need to be considered. The key for pelagic ecosystem researchers will be to identify change, relate the change to environmental characteristics, and ultimately model the impacts of that change.

Background

The pelagic component research team identified two primary questions that could be answered with data collected and compiled under the first five years of Gulf Watch Alaska: a) What are the population trends of key pelagic species groups - whales, forage fish, and marine birds, and b) How can forage fish population trends in PWS be effectively monitored? The rationale for these goals lies with the advantage of existing long-term data sets and knowledge gained in the course of EVOS studies during the last 25 years. The pelagic team has been continuing two of the longest population time series in PWS, on killer whales and marine birds, providing invaluable insight into their dynamics. The EVOS also increased awareness of what is not understood about the pelagic ecosystem, such as variability in forage fish populations (Rice et al. 2007).

The Pelagic component of Gulf Watch Alaska encompasses six projects focused on collecting long-term predator and prey species data from sites centered in PWS. The species covered include killer whales, humpback whales, forage fish, and marine birds. The following gives a brief background on each of the focal species or species groups.

Killer whales (1 project) – Monitoring of killer whales in PWS started in 1984 and provided a high quality data set allowing for detection of injury from the EVOS at the pod and population level. This clearly illustrated the value in long-term monitoring prior to possible perturbations. Both resident ecotype (AB pod) and transient ecotype (AT1 population) killer whales suffered significant mortalities following the EVOS. AB pod is slowly recovering after 22 years but the remaining matriline in the pod have not reached pre-spill numbers. The AT1 population is not recovering and may be headed toward extinction (Matkin et al. 2012a). This research has determined that killer whales are sensitive to perturbations such as oil spills, but as yet, has not documented the long-term consequence (extinction) or the recovery period required for AB pod. As apex predators of fish, particularly salmon, (resident ecotype whales) and other marine mammals (transient whales), killer whales can significantly affect upper trophic dynamics and are a key species for monitoring the pelagic ecosystem. Since killer whales are long lived and slow to reproduce, they reflect long-term trends in the ecosystem as well as being susceptible to immediate perturbations.

Humpback whales (1 project) – In 1946, the International Convention for the Regulation of Whaling regulated commercial whaling of humpback whales. In 1966, the International Whaling Commission prohibited commercial whaling of humpbacks. In June 1970, humpback whales were designated as “Endangered” under the Endangered Species Conservation Act (ESCA). In 1973, the Endangered Species Act (ESA) replaced the ESCA, and continued to list humpbacks as endangered. The Central North Pacific and North Pacific stocks of humpback whales are currently listed as Endangered under the Endangered Species Act, but populations are rebounding and have been steadily increasing in PWS since the end of industrial whaling. Currently there is a petition to de-list humpback whales from the endangered species list. The North Pacific population is now thought to be increasing 5-7% annually (Barlow et al. 2011). Consistent with this increase, the numbers of humpback whales in PWS in summer has increased at about the same rate since the 1980s (Teerlink et al. 2014). Continued monitoring of this predator-prey relationship is an integral piece of the trophic puzzle in PWS.

Forage fish (1 project) – This component focuses on euphausiids, herring, capelin, eulachon, Pacific sand lance, juvenile pollock and juvenile pollock. Because most these species have no direct commercial

value there are few data on their abundance or distribution. However, fluctuations in forage fish abundance can have dramatic ecosystem effects because much of the energy transferred from lower to higher trophic levels passes through a small number of key forage fish species in PWS (Okey and Wright 2004, Springer 2007). This species group has long been noted as an important component of the ecosystem food web, critical to other species (marine birds, larger fish, and marine mammals) (Pikitch et al. 2014). Information is needed on their biology, essential habitats, and population dynamics. Knowing habitats that fish use throughout their life history is paramount before we can begin to understand how biophysical forces will affect their populations. The life history complexities of forage fish, along with minimal baseline data available at the population level, require establishing sampling protocols that provide accurate and precise data and can be repeated as a monitoring tool in the future. Hence, this effort was identified as one of the key goals of the pelagic group.

Marine Birds (3 projects) – There has been long-term monitoring of marine bird populations in PWS since the onset of the EVOS in 1989. An estimated 250,000 marine birds were killed during the EVOS in PWS and the northern Gulf of Alaska (Piatt and Ford 1996). Data collected from 1989 to 2010 indicated that pigeon guillemots (*Cephus columba*) and marbled murrelets (*Brachyramphus marmoratus*) were declining in the oiled areas of PWS (Piatt and Ford 1996, Rice et al. 2007) (Piatt and Ford 1996, Rice et al. 2007), and recent surveys found continued decline or possible stabilization at much lower population sizes (Kuletz et al. 2011, Cushing et al., this report). The primary GWA project monitoring marine birds in PWS is conducted during July, and maintains protocols of the historic data set. In addition to these continued monitoring surveys, researchers are using the long-term data set to examine temporal changes in the marine bird community linked to habitat and climate change. These surveys are among the longest time series available for PWS and offer the most sensitive vehicle to track biological response to environmental change over time.

A second complementary project is focused on monitoring marine birds in PWS from late fall through the winter, the period during which birds face the greatest environmental pressures. Initiated in 2007, this monitoring program places a marine bird observer on regularly scheduled cruises associated with various projects in PWS (EVOS herring and Gulf Watch Alaska humpback whale studies, as well as ADFG shrimp surveys, and Ocean Tracking Network array maintenance). The surveys use USFWS protocols and cover all marine habitats in PWS (bays, passages, and open water). Most marine bird studies occur during summer months, therefore little is known about the habitat associations during winter. Long-term monitoring of marine birds in PWS during winter is needed to understand how changing biophysical factors are affecting spatial and temporal trends in bird abundance, species composition and habitat use.

A third project focuses on birds foraging near the shoreline, an often neglected group of predators for pelagic and benthic ecosystems. These nearshore marine birds include black oystercatchers (*Haematopus bachmani*), cormorants (*Phalacrocorax* spp.), glaucous-winged gulls (*Larus glaucescens*), goldeneyes (*Bucephala* spp.), harlequin ducks (*Histrionicus histrionicus*), mergansers (*Mergus* spp.), pigeon guillemots (*Cephus columba*), and scoters (*Melanitta* spp.). Several agencies have been conducting skiff based surveys for marine birds in the shallow nearshore waters along Katmai, Kenai Fjords, and PWS coastlines ranging from 5 to 20 years (Bennett et al. 2006a). The goal is to continue monitoring existing transects that have continuity with legacy data and work on examining the effects of sampling error and imperfect detection. Another goal is to make recommendations for improving efficiency through sample intensity and frequency.

Pelagic Recommendations

Continue to characterize long-term variability and population trends for all pelagic species being monitored:

- Killer whale population monitoring to determine required time for their recovery and possible extinction due to the oil spill.
- Humpback whale population trend and abundance information in PWS to understand top-down predation on herring and a changing prey field.
- Monitor forage fish as a key component of pelagic ecosystems.
- Seasonal surveys of marine seabirds in PWS and in conjunction with environmental driver component efforts in the Northern GOA (e.g., Seward Line, LCI surveys).

Recommendations for enhancement of current monitoring projects

There are gaps in the current information that would be addressed through further monitoring and process studies that are currently not funded within this program. Current monitoring work leveraged with other studies and technologies has the potential for broader ecological studies that will draw connections between individual species as well as the components of this study

- *Killer whales and humpback whales* - conduct supplemental monitoring with additional focus on feeding ecology using tagging, tissue sampling, and prey sample collection to better inform fisheries managers on consumption rates by large apex predators.
- Integrate existing data from outside this program for other pelagic predator/prey species, including harbor seals, Steller sea lions, and salmon.
- *Forage fish* - due to the nearshore, shallow, and patchy distribution of forage species in the Sound during summer, broad-scale systematic hydroacoustic-trawl surveys for forage fish are not effective or cost efficient. We suggest the following:
 - In addition to aerial shoreline surveys and a validation component with Herring Research and Monitoring program, include acoustic-trawl measurements of prey composition, density, and depth distribution near foraging predators to measure direct linkages to whales and seabird predators (see hotspots below).
 - Support the longest time-series of seabird diet available for the region (i.e., Institute for Seabird Research and Conservation -- Middleton Island) as a forage fish index in the Gulf of Alaska region (Hatch 2013). The continuation of this dataset will be important for informing other ecosystem components with a shorter monitoring history.
- *Integrated hotspot monitoring* - characterize multi-species predator prey aggregations. We have identified a few key areas where pelagic components overlap in time and space, (one example, Montague Strait during September). Integrate environmental conditions into this monitoring.
- Because of evidence for large scale movements of pelagic predators in and out of PWS, expand the scope of pelagic components to other regions of the Northern GOA. This would align our component spatially with other Gulf Watch Alaska components to produce a more complete picture, e.g., repeat EVOSTC work in Cook Inlet, initiate seabird and humpback whale surveys on the GOA shelf (leveraging collaboration with NOAA fisheries stock assessment surveys or continued collaboration with the Seward Line and LCI programs).

References

- Allen, B. M. and R. P. Angliss. 2011 Alaska marine mammal stock assessments, 2010. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-AFSC-223, 292 p
- Ballachey, B. E., D. H. Monson, G. G. Esslinger, K. Kloecker, J. Bodkin, L. Bowen, and A. K. Miles. 2014. 2013 update on sea otter studies to assess recovery from the 1989 *Exxon Valdez* oil spill, Prince William Sound, Alaska. U.S. Geological Survey.
- Barlow, J., J. Calambokidis, E. A. Falcone, C. S. Baker, A. M. Burdin, P. J. Clapham, J. K. B. Ford, C. M. Gabriele, R. LeDuc, D. K. Mattila, T. J. Quinn, L. Rojas-Bracho, J. M. Straley, B. L. Taylor, J. Urbán R., P. Wade, D. Weller, B. H. Witteveen, and M. Yamaguchi. 2011. Humpback whale abundance in the North Pacific estimated by photographic capture-recapture with bias correction from simulation studies. *Marine Mammal Science* 27(4):793–818.
- Bennett, A. J., W. L. Thompson, and D. C. Mortenson. 2006. Vital signs monitoring plan, Southwest Alaska Network.
- Bishop, M.A., J.T. Watson, K. Kuletz and T. Morgan. 2015. Pacific herring consumption by marine birds during winter in Prince William Sound, Alaska. *Fisheries Oceanography* 24(1) 1-13.
- Bishop, M.A. and S.P. Powers. 2013. Top-down regulation by predatory fish on juvenile herring in Prince William Sound. *Exxon Valdez Oil Spill Restoration Project Final Report (Project 10100132-G)*, Prince William Sound Science Center, Cordova, Alaska
- Boveng, P. L., J. L. Bengtson, D. E. Withrow, J. C. Cesarone, M. A. Simpkins, K. J. Frost, and J. J. Burns. 2003. The abundance of harbor seals in the Gulf of Alaska. *Mar. Mammal Sci.* 19(1):111-127.
- Fauchald, P. 2010. Predator–prey reversal: A possible mechanism for ecosystem hysteresis in the North Sea? *Ecology* 91(8):2191–2197.
- Fritz, L., M. Lynn, E. Kunisch, and K. Sweeney. 2008. Aerial, ship, and land-based surveys of Steller sea lions (*Eumetopias jubatus*) in Alaska, June and July 2005-2007. U. S. Dept. Commerce., NOAA Tech. Memo., NMFS-AFSC-183, 70 p. (.pdf, 4.73 MB).
- Gaichas, S. K., K. Y. Aydin, R. C. Francis, and J. Post. 2011. What drives dynamics in the Gulf of Alaska? Integrating hypotheses of species, fishing, and climate relationships using ecosystem modeling. *Canadian Journal of Fisheries and Aquatic Sciences* 68(9):1553–1578.
- Golet, G.H., P.E. Seiser, A.D. McGuire, D.D. Roby, J.B. Fischer, K.J. Kuletz, D.B. Irons, T.A. Dean, S.C. Jewett, and S.H. Newman. 2002. Long-term direct and indirect effects of the ‘*Exxon Valdez*’ oil spill on pigeon guillemots in Prince William Sound, Alaska. *Marine Ecology Progress Series* 241:287-304.

- Heintz, R., J. Moran, J. Vollenweider, J. Straley, and K. Boswell. (n prep). The impact of fishing and predation on Pacific herring production in different states of abundance.
- Heithaus, M. R., A. Frid, A. J. Wirsing, and B. Worm. 2008. Predicting ecological consequences of marine top predator declines. *Trends in Ecology & Evolution* 23(4):202–10.
- Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. *Progress in Oceanography* 49(1-4):257–282.
- Kuletz, K. J., C. S. Nations, B. Manly, A. Allyn, D. B. Irons, and A. Mcknight. 2011. Distribution, abundance, and population trends of the Kittlitz’s Murrelet “*Brachyramphus brevirostris*” in Prince William Sound, Alaska. *Marine Ornithology* 39:97–109.
- Matkin, C. O., J. W. Durban, E. L. Saulitis, R. D. Andrews, J. M. Straley, D. R. Matkin, and G. M. Ellis. 2012. Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (*Orcinus orca*) in the northern Gulf of Alaska. *Fisheries Bulletin* 110:143–155.
- Mundy, P. R. 2005. *The Gulf of Alaska: Biology and Oceanography*. Page 214. P. R. Mundy, editor. Alaska Sea Grant College Program, University of Alaska Fairbanks, Fairbanks.
- Okey, T. A., and B. A. Wright. 2004. Toward Ecosystem-based Extraction Policies for Prince William Sound, Alaska: Integrating Conflicting Objectives and Rebuilding Pinnipeds. *Bulletin of Marine Science* 74(3):727–747.
- Pearson, W. H., R. B. Deriso, R. A. Elston, S. E. Hook, K. R. Parker, and J. W. Anderson. 2011. Hypotheses concerning the decline and poor recovery of Pacific herring in Prince William Sound, Alaska. *Reviews in Fish Biology and Fisheries* 22(1):95–135.
- Peterson, C. H., S. D. Rice, J. W. Short, D. Esler, J. L. Bodkin, B. E. Ballachey, and D. B. Irons. 2003. Long-term ecosystem response to the *Exxon Valdez* oil spill. *Science (New York, N.Y.)* 302(5653):2082–6.
- Piatt, J. F., and R. G. Ford. 1996. Proceedings of the *Exxon Valdez* Oil Spill Symposium: How many seabirds were killed by the “Exxon Valdez” oil spill? Pages 712–719. S. D. Rice, R. B. Spies, D. A. Wolf, and B. A. Wright, editors. American Fisheries Society Symposium 18, Bethesda, Maryland, USA.
- Pikitch, E. K., K. J. Rountos, T. E. Essington, C. Santora, D. Pauly, R. Watson, U. R. Sumaila, P. D. Boersma, I. L. Boyd, D. O. Conover, P. Cury, S. S. Heppell, E. D. Houde, M. Mangel, É. Plagányi, K. Sainsbury, R. S. Steneck, T. M. Geers, N. Gownaris, and S. B. Munch. 2014. The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries* 15(1):43–64.
- Rice, S. D., and M. G. Carls. 2007. Prince William Sound Herring: An updated synthesis of population declines and lack of recovery. “Exxon Valdez” Oil Spill Restoration Project Final Report. National Marine Fisheries Service Juneau, Alaska.

- Rice, S. D., J. R. Moran, J. M. Straley, K. M. Boswell, and R. A. Heintz. 2011. Significance of whale predation on natural mortality rate of Pacific herring in Prince William Sound, “Exxon Valdez” Oil Spill Restoration Project Final Report (Restoration Project #100804). National Marine Fisheries Service Juneau, Alaska.
- Rice, S. D., J. W. Short, M. G. Carls, A. Moles, and R. B. Spies. 2007. The “Exxon Valdez” oil spill. Pages 419–520 R. B. Spies, editor Long-term ecological change in the northern Gulf of Alaska. Elsevier.
- Spies, R. B. 2007. Agents of Ecosystem Change. Pages 171–257 R. B. Spies, editor Long-term ecological change in the northern Gulf of Alaska. Elsevier.
- Spies, R. B., and T. Cooney. 2007. Introduction. Pages 1–9 R. B. Spies, editor Long-term ecological change in the northern Gulf of Alaska. Elsevier.
- Springer, A. M. 2007. Ecosystem Structure. Pages 11–170 R. B. Spies, editor Long-term ecological change in the northern Gulf of Alaska. Elsevier.
- Teerlink, S., O. von Ziegesar, J. M. Straley, T. J. Quinn, C. O. Matkin, and E. L. Saulitis. 2014. First time series of estimated humpback whale (*Megaptera novaeangliae*) abundance in Prince William Sound. *Environmental and Ecological Statistics*. In press.
- Thorne, R. E., and G. L. Thomas. 2007. Herring and the “Exxon Valdez” oil spill: an investigation into historical data conflicts. *ICES Journal of Marine Science* 65(1):44–50.
- Weingartner, T. 2007. The Physical Environment of the Gulf of Alaska. Pages 259–418 R. B. Spies, editor Long-term Ecological Change in the Northern Gulf of Alaska. Elsevier.

RESEARCH SUMMARY: LONG-TERM KILLER WHALE MONITORING IN PRINCE WILLIAM SOUND/ KENAI FJORDS

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Matkin, C. O., J. W. Testa, G. M. Ellis, E. L. Saulitis. 2014. Life History and Population Dynamics of Southern Alaska Resident Killer Whales (*Orcinus orca*). *Marine Mammal Science*. 30 (2): 460-479.

Matkin, C. O., J. W. Durban, E. L. Saulitis, R. D. Andrews, J. M. Straley, D. R. Matkin, and G. M. Ellis. 2012. Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (*Orcinus orca*) in the northern Gulf of Alaska. *Fish. Bull.* 110: 143-155.

Introduction

Both resident ecotype (AB pod) and transient ecotype (AT1 population) killer whales suffered significant mortalities following the *Exxon Valdez* oil spill in 1989. AB pod is recovering after 22 years but has still not reached pre-spill numbers. The AT1 population is not recovering and may be headed toward extinction. This project has determined that killer whales are sensitive to perturbations such as oil spills, but has not yet determined the long-term consequence (which may include extinction) or the recovery period required. We described the damage to AB pod and the AT1 transient group (Matkin et al. 2008) and in recent papers have examined the population status and trends for the fish eating southern Alaska resident population (Matkin et al. 2014) and the two transient (mammal eating) killer whale populations, the AT1 transients and Gulf of Alaska (GOA) transients (Matkin et al. 2012b). All three populations are recognized as unique in the NOAA/NMFS marine Mammal Stock Assessments and data collected in this project has been used to create and revise those assessments. Although our EVOS/Gulf Watch project includes examination of feeding ecology as well as range and habitat use, this report focuses on an update on population dynamics for resident whales and AT1 transients and introduces population analysis of the parapatric Gulf of Alaska transient population. Population monitoring of these populations is key to understanding the role of these predators in the marine environment as well as judging effects of future perturbations.

As apex predators, both fish and mammal eating types of killer whales have the ability to shape the ecosystem through “top down” forcing. Trends in their numbers also reflect the overall health of the system. Killer whales have a direct economic impact in the region as a focus of viewing by a vibrant tour boat industry as well as an intrinsic value as charismatic representatives of the marine environment.

Study Area

Our study area includes the waters of Prince William Sound (PWS) and Kenai Fjords National Park and adjacent outer coastal waters (Figure 3-2).

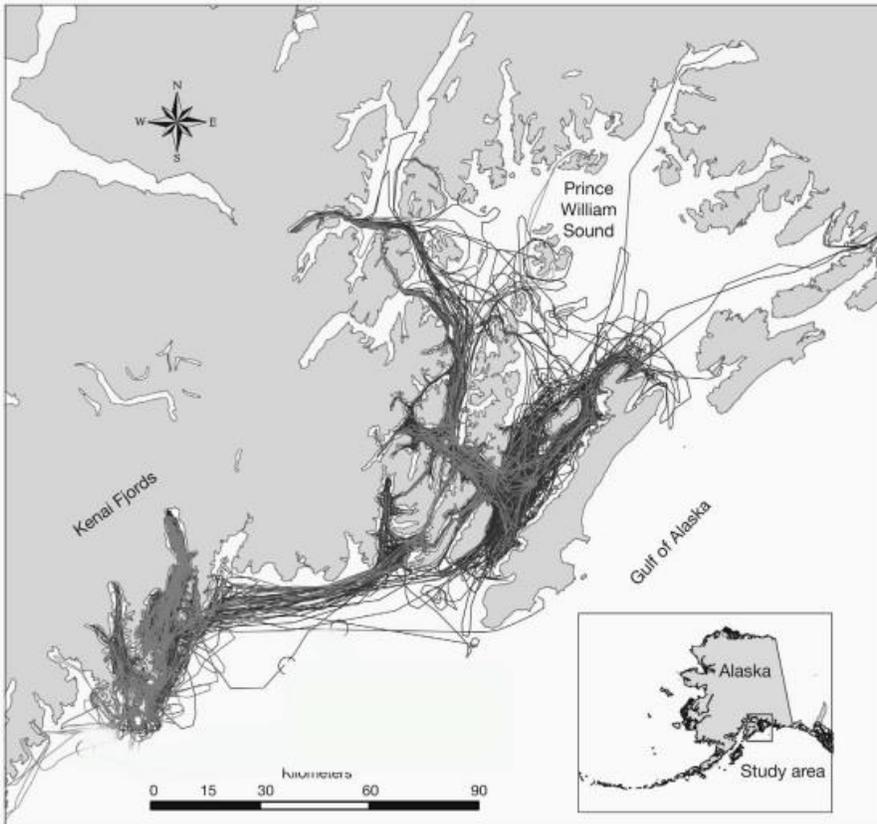


Figure 3-2. Study area and survey tracklines during population studies.

The range of the southern Alaska resident pods described in this study includes the northern Gulf of Alaska (GOA) and inshore waters from southern southeast Alaska through the Kodiak archipelago. The AT1 transients are a separate stock and classified as depleted under the Marine Mammal Protection Act and they currently number only seven individuals (Allen and Angliss, 2010). The home range of the AT1 transient population is much more restricted and extends from Cape St Elias to the outer coast of the Kenai Peninsula. The GOA transient population ranges from the outside waters of northern British Columbia across the Gulf of Alaska to the Kodiak archipelago (Matkin et al. 1999, Scheel et al. 2001). All three of these populations are acoustically and genetically distinct and do not associate although their ranges overlap and all use our study area regularly.

Methods

The basis for our population monitoring work and all other aspects of the project is the photo identification of individual whales. The techniques used to approach and photograph the whales were consistent over the duration of the study. Whales were approached from the left side or from behind to a lateral distance of 15-30 m. Photographs were always taken of the left side of each whale showing details

of the dorsal fin and grey saddle patch. In the most useful photographs the whale filled at least 50% of the frame. We attempted to obtain photographs of all whales in each encounter, however, this was not always possible due to conditions of weather and/or light, and for larger groups it often required multiple encounters to completely photograph all whales.

Our analytical techniques varied based on the characteristics of the population. Our detailed population dynamics analysis of the southern Alaska resident population is possible because of attributes that are not shared by transient types. Resident killer whales are relatively accessible with a high probability of encountering individuals on an annual basis, and they travel in maternal groupings that change composition only as a result of births or deaths. These permanent associations facilitate the repeated identification of individuals and allow accurate annual tracking of individuals within maternal groups for a substantial segment of the population.

Our most recent analysis of resident population dynamics required an annual census that was initiated in 1984 and continued through 2010, though effort declined following 2005 and some pods were not seen in all of the last five years of the years reported on. We annually attempted to photographically identify each individual whale in the 10 pods that comprised our sample. Due to anomalous mortalities following the *Exxon Valdez* oil spill (EVOS) the well-described AB pod was examined separately in greater detail (Matkin et al. 2008).

Because of its limited range, small population size and the consistent re-sightings of subgroups and individuals, the population dynamics of the AT1 population have been monitored directly from annual photographic data since 1984 (Matkin et al. 2008). However, for the parapatric GOA transients, with less frequent re-sightings of individuals, a larger, wide ranging population, and some fluidity in group structure, it was impossible to directly track births and deaths. For these transients, a mark-recapture sampling approach was required to estimate abundance and assess population changes. We first tested our Bayesian mark-capture analytical techniques on AT1 transient population data to judge its accuracy and then applied the refined techniques to the GOA transients (Matkin et al. 2012b). Thus, we were able to monitor three killer whale populations representing two different ecotypes that all use the waters of PWS/Kenai Fjords.

Key Findings

One resident pod, the AB Pod, and one transient population, the AT1 Group, suffered losses of 33 and 41 percent, respectively, in the year following the spill. Sixteen years after 1989, AB Pod had not recovered to pre-spill numbers (Figure 3-3).

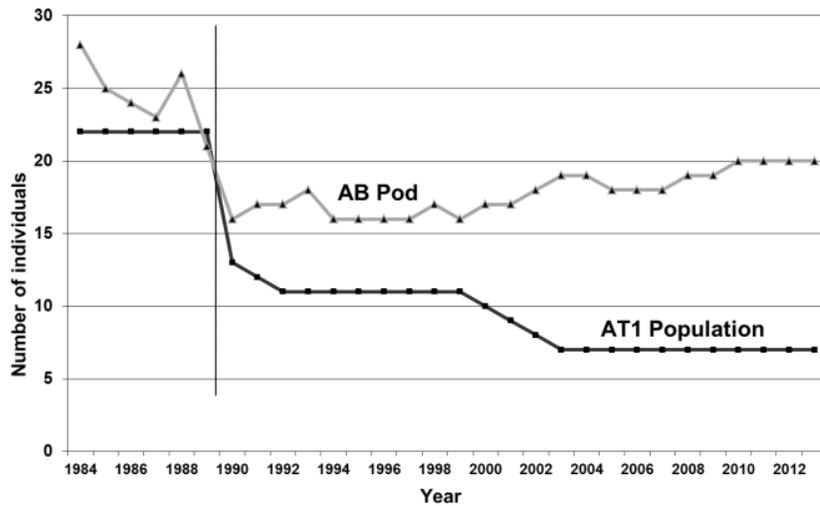


Figure 3-3. Numbers of whales in AB pod and AT1 population 1984-2013 (tracks only portion of AB pod that has remained an independent pod as described below)

Moreover, its rate of increase was significantly less than that of other resident pods that did not decline at the time of the spill. Recovery of the AB Pod after 1990 was unexpectedly slow (average of 1.6% per year) compared to population increases in other resident pods in PWS (average 3.2% per year), and was the result of 2 factors: (1) abnormal mortalities of reproductive females and juveniles in the year following the spill; and (2) continued unexpected mortalities in years following the spill. In recent years the growth has stalled at 20 individuals in the portion of AB pod that remains an independent pod. Part of the original AB pod, the AB25 subgroup, split off and has traveled with AJ pod since the 1990s and is considered by definition, a separate pod.

The lack of recovery of AB Pod can be largely attributed to the loss of young adult females, which reduced the number of reproductive females by half (from 6 to 3), and the loss of juveniles, such that fewer animals matured to replace the reproductive females that died. As a result, the annual birth rate in AB Pod since the EVOS has been far lower than in other resident pods, and significantly lower than expected. This was accompanied by a sharp decrease in reproductive potential (number of calves expected to be born during the next generation) for AB Pod, which was significantly higher before (1984 to 1988) than after (1989 to 2005) the EVOS (Student's *t*-test; $t = 16.5$, $p < 0.001$).

The AT1 population, which was stable at 22 whales from 1984-1988, lost 9 members following the spill and continued to decline and remain at 7 individuals. They are not a “pod” (as in the case of AB pod) but a separate and unique population. Although there may be other contributing factors, the loss of AT1 individuals, including reproductive-age females, following the EVOS accelerated the population’s trajectory toward extinction. The synchronous losses of unprecedented numbers of killer whales from 2 ecologically and genetically separate groups and the absence of other obvious perturbations strengthens the link between the mortalities and lack of recovery, and the EVOS.

Our trend analysis revealed an abrupt decline in the abundance of the AT1 transient population following the EVOS in 1989 (Matkin et al. 2012b), corroborating earlier interpretations of photo-identification data (Matkin et al. 2008). This decline in abundance correlates with a spike of lower apparent survival from 1989-1990 and is almost certainly due to mortality, as supported by the low estimated rates of temporary emigration, high capture probabilities and the lack of evidence of movement into other areas (Matkin et al. 1999, 2008). Using the same type of analysis, there was no detectable decline in the GOA transient abundance over the period of study (Figure 3-4).

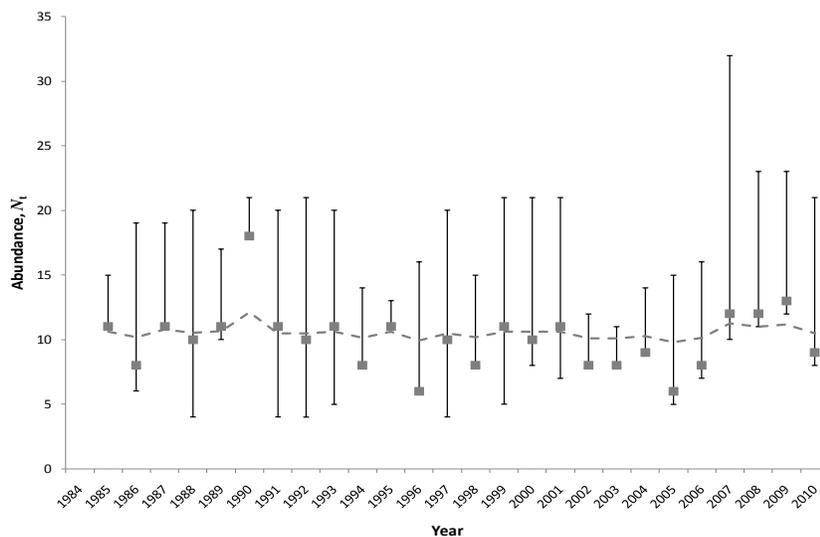


Figure 3-4. Estimates of abundance for Gulf of Alaska (GOA) transient killer whales (*Orcinus orca*) in the PWS/Kenai Fjords study area. The broken horizontal line represents the trend given by a change-point model.

As occasional visitors to the PWS/Kenai Fjords region, and due to their more extensive range, GOA transients have likely been less affected by local changes to habitat and prey as well as having escaped immediate exposure to the EVOS. While the AT1 transients appear dependent on harbor seals, Dall’s porpoise and harbor porpoise, documented prey for GOA transients are notably different in that Steller sea lion (*Eumetopias jubatus*) are of great importance and not found in the AT1 diet (Saulitis et al. 2000, Heise et al. 2003, Maniscalco et al. 2007). As the AT1 transients head toward extinction, it is possible that the GOA transients may move in to fill that niche. Sightings of GOA transients have increased in recent years.

We conducted a detailed population analysis of the southern Alaska resident population (other than AB pod) and established characteristics of the population and a population growth rate (Matkin et al. 2014). The number of whales in 10 pods that were seen from 1984 to 2005 increased from 121 whales to 240 at a mean annual growth rate of 3.4%. The seven pods seen from 1984 to 2010 increased from 82 to 152 at a mean annual rate of 2.6% (Figure 3-5). Because three of the pods (AF05, AF22, AG) center their range in southeastern Alaska (Matkin et al. 1997, 1999) and were often out of our study area, they could not be tracked consistently between 2005 and 2010 and our examination of detailed population characteristics is

based on the 1984-2005 data from all pods. These three southeastern Alaska pods were also the fastest growing pods in the population.

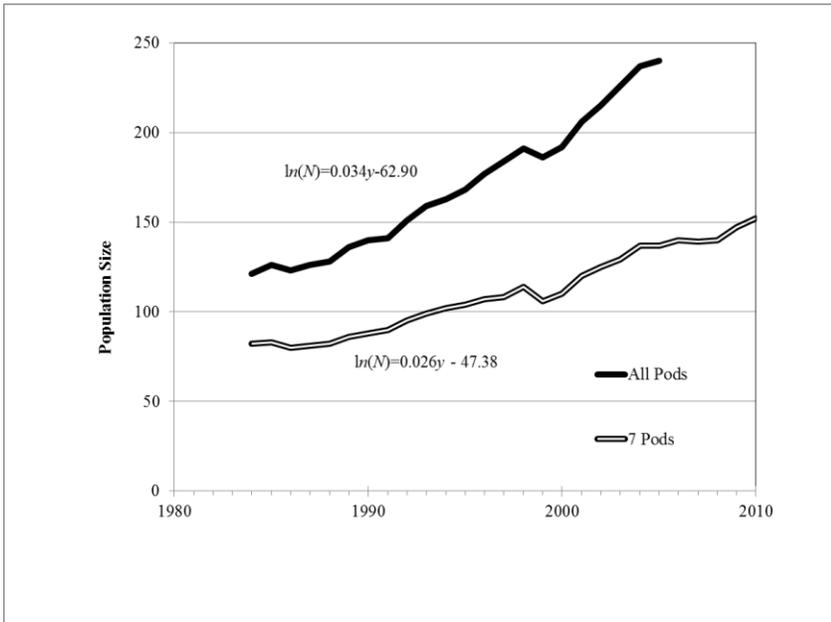


Figure 3-5. Population trend for 10 pods of southern Alaska resident killer whales from 1984 to 2005 (top) and for seven of those pods that were monitored through 2010.

Median age of first reproduction for females was 13.3 years and median age for onset of male sexual maturation (determined by fin growth was 12.4 years. (Figure 3-6)

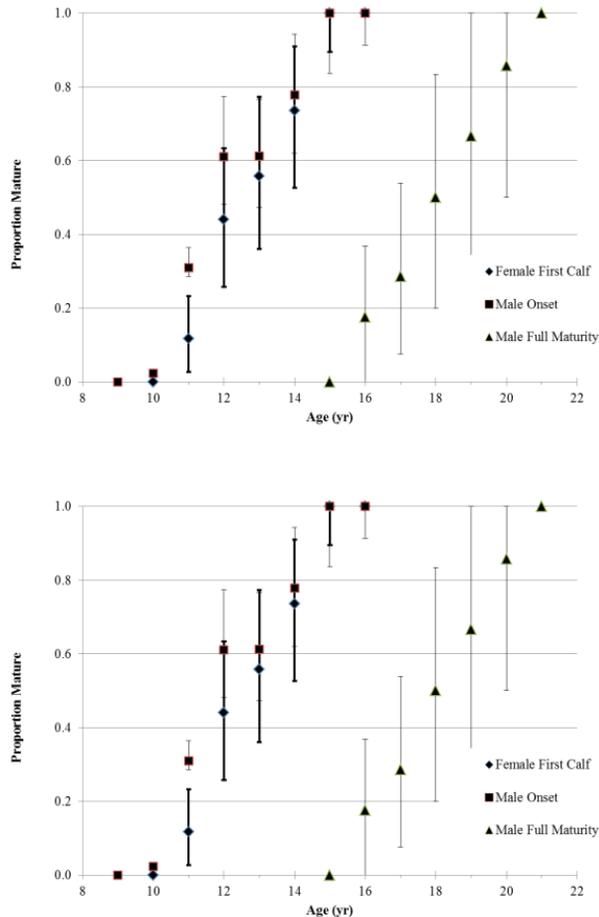


Figure 3-6. Age of sexual maturity (first calf) in known-age females and males (onset of dorsal fin growth) and male full maturity as judged by dorsal fin development for southern Alaska resident killer whales.

Calves were produced at intervals of 2-14 years, but most were separated by 3-7 years (mean 4.9). The number of calves produced by each individual per year declined with age due to the longer calving intervals and apparent onset of senescence. Few calves were produced after age 45. Survivorship for both males and females conformed to the classic mammalian U-shaped curve indicating that the youngest and oldest animals experienced the highest mortality; however, the curve was narrower for males than females with a significant uptick in mortality for males in the 30-41 year range and for females in the 50-54 year range, indicating a longer lifespan for females.

Because there have not been marked changes in the rate of growth of our southern Alaska resident population (other than AB pod) during the period of this study, it is difficult to assess the role of various population parameters in response to changing conditions. The decline in AB pod was due to the EVOS

(Matkin et al. 2008) and not reflective of changes in natural conditions. Other researchers have suggested that slow steady growth of resident killer whale populations with periods of higher mortality due to unfavorable conditions or catastrophes may be the typical pattern (Olesiuk 2005). However, responses to negative long-term changes in carrying capacity may be more complex. In this regard, the killer whale cannot be compared to terrestrial predators such as the grey wolf (*Canis lupus*) which has an early age of first reproduction (2-4 yr), the ability under favorable conditions to produce multiple offspring (4-8 per litter), and a relatively short lifespan (8-16 yr) (Mech 1970, Peterson et al. 1984, Fuller 1989). These characteristics allow wolf populations to respond relatively quickly to changes in prey density or other environmental factors and create the potential for relatively rapid shifts in abundance of predator and prey. Southern Alaska resident killer whale life history parameters indicate more modulated changes in numbers and less dramatic shifts in predation pressure since life history parameters constrict population response (Cole 1954, Testa et al. 2012). This implies a slower ability to recover following a catastrophic event such as an oil spill (Matkin et al. 2008) or other perturbations as well as a slower response to improving conditions.

There may have been an increase in carrying capacity for southern Alaska resident killer whales in recent decades. Salmon populations in the region have rebounded from low population levels recorded during the period from 1945 to 1975 that appear linked to the Pacific Decadal Oscillation (Kaeriyama et al. 2009). Coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*Oncorhynchus tshawytscha*) appear to be primary prey for this population (Saulitis et al. 2000) (C. Matkin unpublished data). In PWS and the Copper River the average permitted catch (based on run strength) for Chinook salmon from 1950 to 1975 was 17,576 (SD 7,228) fish, and for coho salmon 231,500 (SD 131,000) fish which essentially doubled during the 1976 to 2010 period to 36,342 (SD 15,695) Chinook salmon, and 476,228 (SD 242,000) Coho salmon. The substantial increase in southern Alaska resident killer whales observed during the period of our study may be a result of the increased abundance of salmon species important in killer whale diet. With continued monitoring we would expect to see increased mortality and a leveling of the southern Alaska resident population.

During the 1984-2005 period, the southern Alaska resident killer whale population increased at an average annual rate of 3.5%, which is probably representative of the population at r-max. This suggests a recovery from earlier perturbation or more likely, changes in carrying capacity, specifically increases in recent decades of annual returns of Chinook and Coho salmon. Healthy stocks of these salmon species are essential for the continued success of the southern Alaska resident killer whale population.

References

- Allen, B. M. and R. P. Angliss. 2010. Alaska Marine Mammal Stock Assessments, 2009. U.S. Dept. of Commerce, NOAA Technical Memorandum. NMFS-AFSC 206. 276 p.
- Cole, L. C. 1954. The population consequence of life history phenomena. Quarterly Review of Biology 29(2):103-137.
- Fuller, T. K. 1989. Population dynamics of wolves in North-Central Minnesota. Wildlife Monographs:105.

- Heise, K., L. G. Barrett-Lennard, E. Saulitis, C. Matkin, and D. Bain. 2003. Examining the evidence for killer whale predation on Steller sea lions in British Columbia and Alaska. *Aquatic Mammals* 29(3):325–334.
- Kaeriyama, M. H., H. Seo, and H. Kudo. 2009. Trends in run size and carrying capacity of Pacific salmon in the North Pacific ocean. *Fisheries Commission Bulletin* 5:293–302.
- Maniscalco, J. M., C. O. Matkin, D. Maldini, D. G. Calkins, and S. Atkinson. 2007. Assessing Killer Whale Predation on Steller Sea Lions From Field Observations in Kenai Fjords, Alaska. *Marine Mammal Science* 23(2):306–321.
- Matkin, C. O., J. W. Durban, E. L. Saulitis, R. D. Andrews, J. M. Straley, D. R. Matkin, and G. M. Ellis. 2012. Contrasting abundance and residency patterns of two sympatric populations of transient killer whales (*Orcinus orca*) in the northern Gulf of Alaska. *Fisheries Bulletin* 110:143–155.
- Matkin, C. O., G. M. Ellis, E. L. Saulitis, L. G. Barrett-Lennard, and D. R. Matkin. 1999. Killer whales of southern Alaska. Page 96. *North Gulf Oceanic Soc.*, Homer, AK.
- Matkin, C. O., D. R. Matkin, G. M. Ellis, E. L. Saulitis, and D. McSweeney. 1997. Movements of resident killer whales in southeastern Alaska and Prince William Sound, Alaska. *Marine Mammal Science* 13:469–475.
- Matkin, C. O., J. Ward Testa, G. M. Ellis, and E. L. Saulitis. 2014. Life history and population dynamics of southern Alaska resident killer whales (*Orcinus orca*). *Marine Mammal Science* 30(2):460–479.
- Matkin, C., E. Saulitis, G. Ellis, P. Olesiuk, and S. Rice. 2008. Ongoing population-level impacts on killer whales *Orcinus orca* following the ‘Exxon Valdez’ oil spill in Prince William Sound, Alaska. *Marine Ecology Progress Series* 356(1983):269–281.
- Mech, C. O. 1970. *The wolf, the ecology and behavior of an endangered species*. Doubleday, New York, New York, USA.
- Olesiuk, P. F. 2005. Life history and population dynamics of northern resident killer whales (*Orcinus orca*) in British Columbia. Research Document 2005/045. Fisheries and Ocean Canada, Nanaimo, B.C. Canada.
- Peterson, R. O., J. D. Woolington, and T. N. Bailey. 1984. Wolves of the Kenai Peninsula, Alaska. *Wildlife Monographs* (88):3–52.
- Saulitis, E. L., C. O. Matkin, K. Heise, and H. Fay. 2000. Foraging strategies of sympatric killer whale (*Orcinus orca*) populations in Prince William Sound, Alaska. *Marine Mammal Science* 16:94–109.
- Scheel, D., C. O. Matkin, and E. L. Saulitis. 2001. Distribution of killer whale pods in Prince William Sound, Alaska over a thirteen-year period, 1984–1996. *Marine Mammal Science* 17:555–569.

Testa, J. W., K. J. Mock, C. Taylor, H. Koyuk, J. R. Coyle, and R. Waggoner. 2012. Agent-based modeling of the dynamics of mammal-eating killer whales and their prey. *Marine Ecology Progress Series* 466(2003):275–291.

RESEARCH SUMMARY: LONG-TERM MONITORING OF HUMPBACK WHALE PREDATION ON PACIFIC HERRING

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Straley, J., J. Moran, J. Vollenweider, K. Boswell, R. Heintz, T. Quinn, and S. Rice. (*In Review for Fisheries Oceanography*). Seasonal presence and potential influence of foraging humpback whales upon Pacific herring wintering in the Gulf of Alaska.

Moran, J., R. Heintz, J. Vollenweider, and J. Straley. (*In Review for Fisheries Oceanography*). Regional variation in the intensity of humpback whale predation on Pacific herring in the Gulf of Alaska.

Introduction

In FY 2005, a group of scientific investigators collaborated to integrate information about the herring population in Prince William Sound (PWS) and identify factors contributing to its lack of recovery. Top down control was identified as probably having more influence in PWS than on other herring stocks. Of the two top factors, disease and predation, there was recent evidence that disease continues to have episodic events affecting the population, but there were insufficient data to assess the role of predators in limiting recovery. Future population assessment modeling would need to have better quantification on the significance of predation. Predation by marine mammals has been hypothesized as a factor in the failure of the PWS herring population to rebound (Rice and Carls 2007).

The humpback whale (*Megaptera novaeangliae*) population in the north Pacific is growing at about 5% per year and is estimated to be in excess of 20,000 individuals (Barlow et al. 2011). This has prompted concern (Morishita 2006, Clapham et al. 2007, Gerber et al. 2009) that whales may be competing for fishery production either directly by consuming commercially valuable species or by consuming prey resources used by harvested species. Their large size and relatively high metabolic rates have warranted concern that humpback whales could be removing significant biomass from some locally harvested stocks.

Impacts of humpback whale foraging on local populations may be particularly acute when humpback whales exploit forage fish that congregate in predictable locations, as is the case for overwintering herring (Sigler and Csepp 2007). In Alaska, humpback whales have been observed foraging on overwintering congregations of herring in Lynn Canal, Sitka and PWS, but the impact of the whales on these populations is unknown. Currently, the herring populations in Lynn Canal and PWS are depressed and have been closed to fishing for more than a decade. In contrast, the Sitka Sound herring population appears healthy and currently harvest levels are near historic highs.

We address the significance of whale predation on herring by relating the potential biomass removed in each location to estimates of herring abundance. To estimate the biomass removed we combined constructed daily attendance models and observed diets with published data on whale size and metabolic demands. Daily consumption rate models were constructed for each location. Parameter values for the models were varied in order to provide low and high-end estimates that bracketed the range of all potential estimates.

Study Area

We monitored humpback whales at three locations in the Gulf of Alaska (Prince William Sound, Lynn Canal, and Sitka Sound) where predation on large shoals of Pacific herring (*Clupea pallasii*) occurs during the fall and winter months (Figure 3-7).

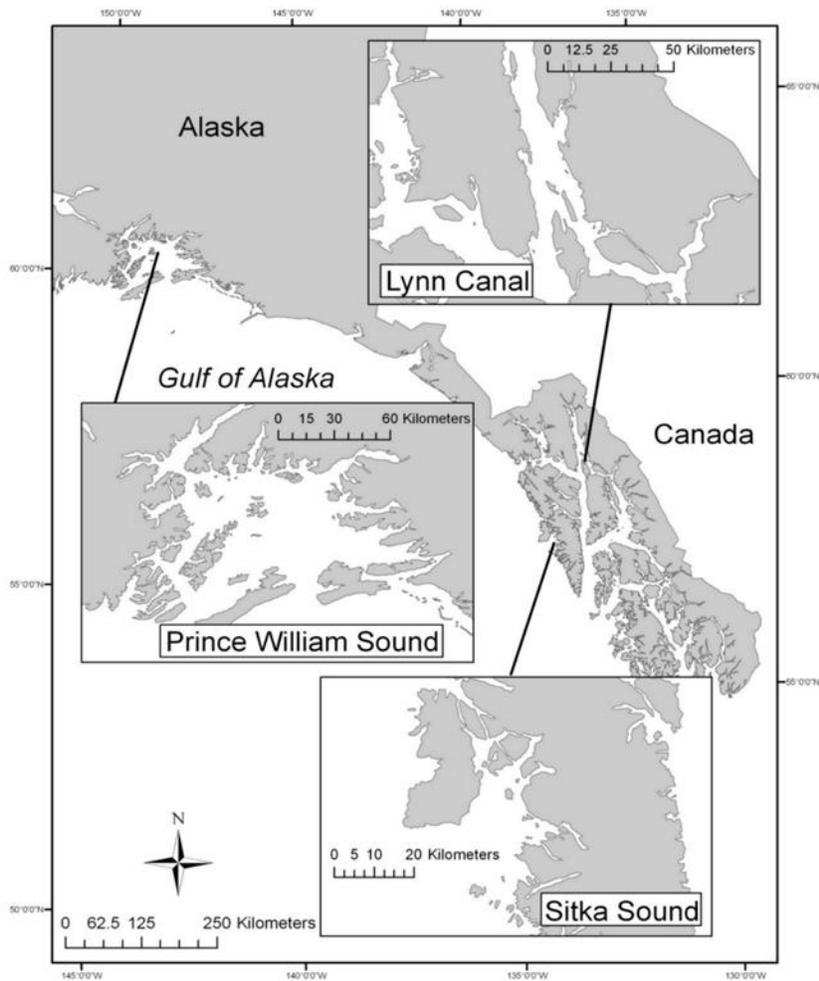


Figure 3-7 Locations of Prince William Sound, Lynn Canal, and Sitka Sound study areas in the Gulf of Alaska.

Methods

We estimated the impact of humpback whales on herring from Lynn Canal, Sitka Sound and PWS for the winters of 2007-2008 and 2008-2009. Direct measurements of ingestion rates for humpback whales are difficult; therefore, estimates of consumption were derived from the allometry between whale size and metabolic requirements. The consumption model we employed combined estimates of whale metabolic rates (Wahrenbrock et al. 1974, Perez and Mcalister 1993, Acquarone et al. 2006, Leaper and Lavigne 2007), sizes (Nichol and Heise 1992), diets, seasonal trends in attendance, and numbers (Huggins closed-capture model) (White and Burnham 1999) with the energy content of overwintering herring. The study period spanned September 15 to March 15, the time frame in which we observed herring begin to aggregate and form overwintering shoals. We estimated the biomass removed for each location and winter using two different modeling scenarios. Each of these scenarios represented a different combination of whale abundance and estimators of humpback metabolic rates. Dividing the resulting range of values with estimates of total population biomass yields a measure of the intensity of humpback whale predation on the herring populations in each location. This ratio, referred to here as predation intensity, is not meant to indicate the actual proportion of the biomass consumed by whales, but rather as an indicator of the scale of whale predation.

Results

Whale Observations

The movement and distribution of whales from fall to winter varied for each study area during study years 2007/08 and 2008/09 (Figure 3-8). Groups of whales moved into PWS in early fall through Montague Strait (Figure 3-8) and continued moving into the inner reaches of the Sound as winter progressed. In Lynn Canal, groups of whales were scattered, with no pattern of movement discerned across the study area (Figure 3-8). Groups of whales were feeding in middle of Sitka Sound early in the season and moved to northern Sitka Sound later in winter when herring were present in deep trenches (Figure 3-8).

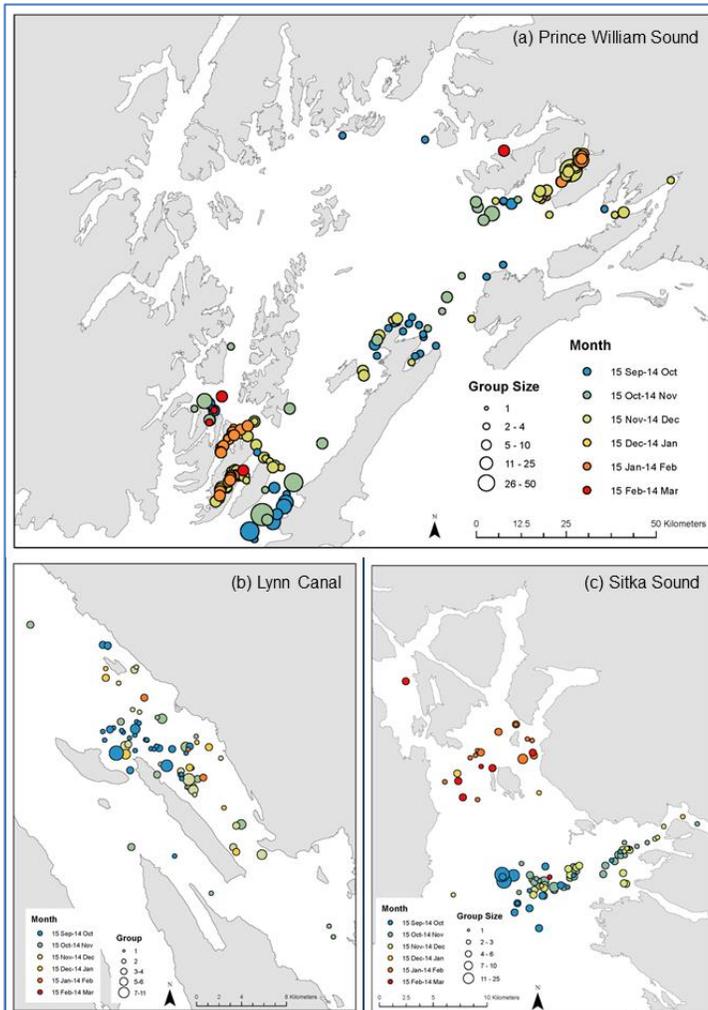


Figure 3-8 Prince William Sound (b) Lynn Canal, and (c) Sitka Sound. Each map depicts the groups of humpback whales seen across the fall and winter by month. Sightings were combined across the study years 2007/08 and 2008/09.

Humpback whales were generally most abundant across locations in the first half of each year's survey. Timing of peak abundance depended on both year and location. In Sitka Sound the peak abundance of whales was observed in November during the first survey (2007-2008) and in October during the second survey (2008-2009) (Figure 3-9). Peak abundance in Lynn Canal tended to be earlier, occurring in September in the first survey and October during the second survey. In PWS whales remained at high abundance throughout the fall of the second survey and only began declining after December (Figure 3-9). While the daily abundance for first survey in PWS was not estimated, the largest number of whales was observed in December.

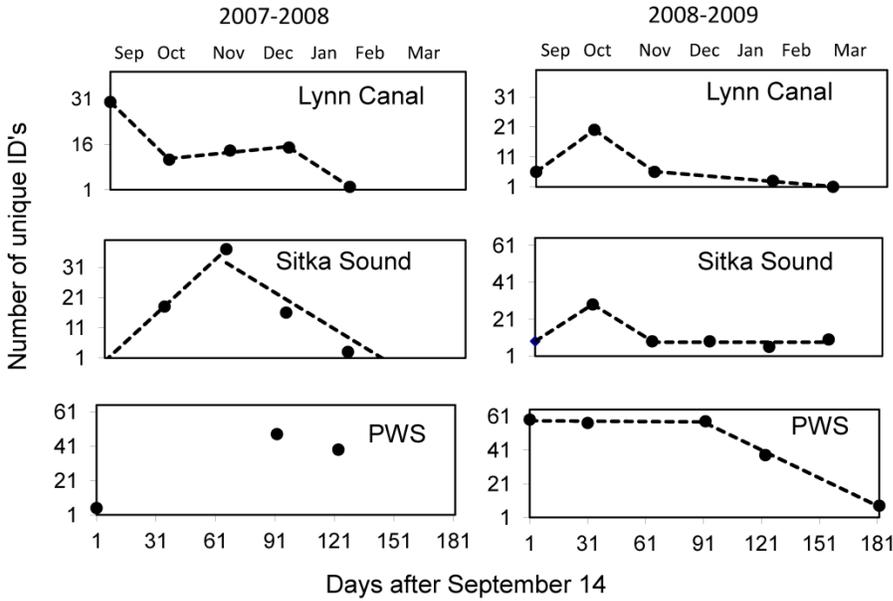


Figure 3-9. Attendance patterns of humpback whales in Prince William Sounds, Lynn Canal and Sitka Sound for the two study years during the fall and winters of 2007-2009. Points show the number of unique whales identified in each location during each month. The attendance pattern for Prince William Sound in 2007/08 was not modeled because only three surveys were conducted over a limited spatial area.

The relative abundances in the Huggins closed-capture models (Table 3-1) generally agreed with that of the numbers of unique individuals (Table 3-2) except that the Huggins model predicted abundance to be highest in SS in 2007/08.

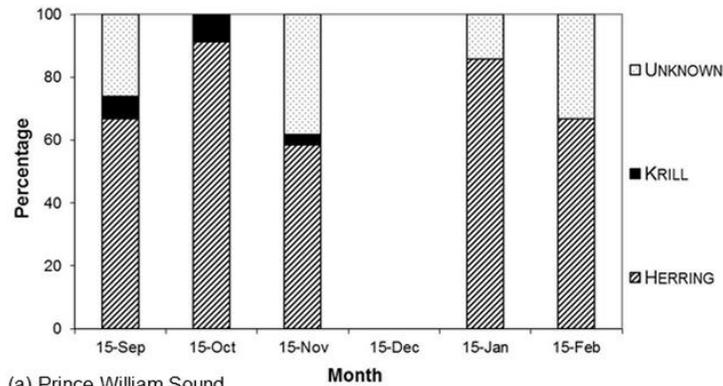
Table 3-1. Huggins closed-capture modeling results for Prince William Sound (PWS), Lynn Canal (LC), and Sitka Sound (SS) and the number of unique individuals identified in each area. Standard errors of the abundance estimates are in parentheses, lower and upper lower bounds of the 95% confidence interval are given in brackets.

	2007/08 Estimate	2008/09 Estimate
PWS	64.2 (30.67)	134.8 (11.9)
Individuals	81	147
LC	51.6 (6.4)	35.4 (8.7)
Individuals	42	24
SS	95.3 (24.2)	67.8 (11.9)
Individuals	70	71

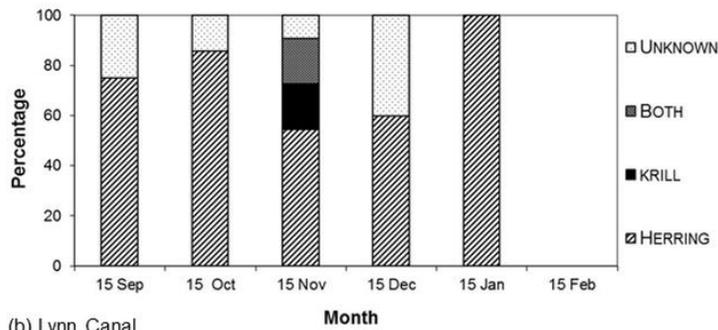
Overall, there was much more foraging effort exerted by humpback whales in Prince William Sound than the other areas as a result of their prolonged period of peak abundance there. The total number of humpback whales present in Prince William Sound over the 182 survey days in (2008-2009) was more than threefold that of Sitka (18,719 vs. 5,114 whale days) and more than nine-fold that of Lynn Canal (2,019 whale days).

Prey selection

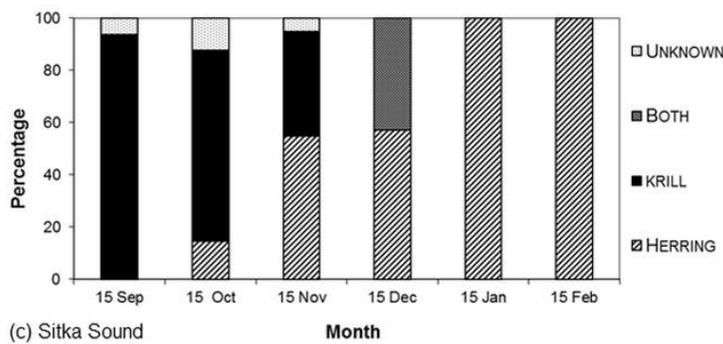
Humpback whale prey choice depended on the season and location sampled. In Lynn Canal and PWS whales foraged almost entirely on herring in the first months of the survey. While few whales were observed foraging on herring after December in Lynn Canal, whales in PWS continued to focus on herring throughout the entire survey period. In contrast, humpback whales in Sitka focused on krill early in the winter and switched to herring later (Figure 3-10).



(a) Prince William Sound



(b) Lynn Canal



(c) Sitka Sound

Figure 3-10. Proportion of prey type observed by groups (N=163) of feeding humpback whales in Prince William Sound each month during the combined fall and winters, 2007/08 and 2008/09. (b) Proportion of prey type observed by groups (N=28) of feeding humpback whales in Lynn Canal each month during the combined fall and winters, 2007/08 and 2008/09. (c) Proportion of prey type by groups (N=108) of feeding humpback whales in Sitka Sound each month during the combined fall and winters, 2007/08 and 2008/09.

Predation intensity

Predation intensity was estimate using our consumption models. In Lynn Canal most of the whale foraging effort on herring was focused on the beginning of the survey period when whales were abundant and herring were relatively scarce. Overall, humpback whales consumed between 732-1,987 tonnes of herring in 2007-2008 and 501-1,335 tonnes in 2008-2009 (Table 3-2). In November 2007 whales consumed approximately one-third of the total biomass consumed over the study period. Comparing whale consumption with the herring biomass present in November yielded estimates of predation intensity ranging between 2.2% and 6.0%. In December, the mass of herring consumed declined as whales departed, but herring biomass increased. Thus, predation intensity dropped to less than 1% regardless of the modeling scenario. After December no whales were observed consuming herring.

Table 3-2 Range of estimated herring biomass removed from Lynn Canal from consumption models (LC), Sitka Sound (SS), and Prince William Sound (PWS) under the low-end and high-end models.

Location	Survey Period	Whale Days	Herring Consumed (Tonnes)	Total Herring Biomass (Tonnes)	Predation Intensity
LC	07-08	2940	732-1,987	1,461	50-136%
	08-09	2019	501-1,335	499	100-267%
SS	07-08	7,190	1,018-2,776	101,209 ²	1-3%
	08-09	5,114	813-2,168	108,192 ²	1-2%
PWS	07-08	8,915	2,639-7,443	9,650 ¹	27-77%
	08-09	18,719	4,388-12,989	20,737 ¹	21-63%

¹Steve Moffitt, personal communication, Alaska Department of Fish and Game

²Sherri Dressel, personal communication, Alaska Department of Fish and Game

In Sitka Sound humpback whales were abundant in fall but their foraging effort focused on krill. Consequently, predation intensity on herring was very low. In absolute terms whales consumed about the same tonnage of herring from Sitka Sound as they did in Lynn Canal (Table 3-2) even though whales were more abundant in Sitka Sound. In Sitka Sound humpback whales consumed 1,018-2,776 and 813-2,168 tonnes in 2007-2008 and 2008-2009, respectively (Table 2). However, this represented less than 3% of the total biomass of herring available. The biomass consumed was far less than the biomass removed in the Sitka Sound sac roe harvest: 14,616 and 15,012 tonnes in 2007 and 2008, respectively (S. Dressel, Alaska Department of Fish and Game, USA, pers. comm.)(ADFG 2012).

Whales foraged in large numbers over much of the winter in PWS, resulting in significant predation intensity. In absolute terms, whales consumed between 2,639 –7,443 tonnes in 2007-2008 representing a predation intensity of 27%-77%. In, 2008-2009 whales consumed between 4,388 and 12,989 tonnes and predation intensities ranged between 21% - 63% of the total biomass present in spring 2008. For comparison the last harvest of herring from PWS was 3,904 tonnes in 1998 (ADFG 2010).

Conclusions

By examining humpback whale interactions with three wintering herring populations we determined that humpback whales had the greatest impact on PWS Herring. The number of whales was greatest in PWS; they foraged on herring for a longer period of time into the winter, and removed a greater percentage of the available biomass of herring. Whales in Lynn Canal foraging on herring peaked in fall; whale numbers dropped off considerably after October. Whales in Sitka Sound were more abundant than Lynn Canal but they foraged predominately on krill, even though the Sitka herring population is far more robust than the other populations. In 2007 to 2009, studies concluded that the herring biomass consumed in PWS approximated the biomass lost to natural mortality over winter as projected by age structured stock assessments, suggesting they are the dominant top down force in herring removals, at least for the years covered. These data indicate that the focused predation in PWS can exert top down controlling pressure, but whale populations are not a ubiquitous threat to other forage fish populations

It is important to recognize that predation intensities reported do not reflect the true proportion consumed. As in any stock assessment, estimates of spawning stock biomass in each location only indexes a portion of the total number of herring present. Spawning stock biomass does not include immature fish that did not spawn; those fish may not be located with spawners or foraging whales. In addition, spawning stock biomass does not account for those age classes that are too young to be sampled by spawning ground surveys. In addition it is important to note that whales are not suspected of causing population declines in Lynn Canal or PWS. The herring population in Lynn Canal was closed to fishing in 1981. The cause for its failure is unknown, but habitat loss and overfishing have been identified as important factors (Carls et al., 2008). In PWS the herring population crashed following an epizootic outbreak of viral hemorrhagic septicemia (VHS) (Rice and Carls 2007).

Impacts of whale predation on Lynn Canal herring

Seasonal changes in the abundance of herring in Lynn Canal obscure the impact of whales on this population. Monthly acoustic surveys conducted during the winter of 2007-2008 revealed a pattern consistent with that of Sigler and Csepp (2007), which indicates a biomass of herring in midwinter (December to February) that swamps the local spawning stock biomass. It is unclear if the large winter aggregation represents a mixture of discrete spawning stocks or the local Lynn Canal spawning stock is a component of a much larger population.

Impacts of whale predation on Sitka Sound herring

The consumption of Sitka Sound herring by humpback whales is underestimated here. Whale predation on herring in Sitka Sound was not significant until late in the survey, when herring began staging prior to spawning. It is not known where the herring were located in fall to early winter or if whales were foraging on them before they arrived in Sitka Sound. The number of unique whales increased slightly in February 2009 when herring arrived in Sitka Sound, presenting the possibility that some individuals were traveling with the herring. Consequently, some level of predation occurred outside our study area. Nevertheless, predation intensity would have to increase tenfold to equal that of the other locations.

Impacts of humpback whale predation on PWS herring

Estimates of predation intensity in PWS provide the best evidence for humpback whales limiting the recovery of a depressed herring population. Whales removed a biomass approximating the State of Alaska's Guideline Harvest Level for herring in Prince William Sound. Between 2001 and 2006 natural

mortality over winter accounted for the loss of 1,800 to 5,500 tonnes of adult herring (Marty et al. 2010). The biomass consumed by humpback whales over the winters of 2007-2008 and 2008-2009 falls within this range, suggesting that humpback whales account for the majority of the winter mortality of adult herring in PWS. While the hypothesis that humpback whale predation was a factor limiting the recovery of herring in 2007-2009, preliminary evidence from further studies starting in 2011 in PWS (not yet complete), are uncertain whether whale consumption adds significantly to current levels of mortality and if herring mortality is currently unsustainable.

Summary

During the fall and winters of 2007 to 2009, we reported that high numbers of whales were present and primarily feeding on herring in Prince William Sound (EVOSTC project PJ090804). This consumption of herring, estimated to be 20% of the adult herring biomass, accounted for the majority of the estimated winter mortality of adult herring in Prince William Sound (Rice et al. 2010). While the hypothesis that humpback whale predation might be a factor limiting the recovery of herring is plausible under the estimates provided here, the ecosystem is not static (Heinz et al. in prep). Preliminary results for studies starting in 2011 (EVOSTC project 13120114-N) indicate a changing prey field, which may reflect broader ecosystem changes. Current population trends suggest increasing whale abundance is coincident with a reorganization of the apex predator community, dramatic declines in harbor seals, Steller sea lions and sea birds (Allen and Angeliss 2011, Fritz et al. 2008, Boveng et al. 2003). How this reorganization will reverberate throughout the Prince William Sound ecosystem in light of a changing prey field is unknown. Listed under the Endangered Species Act, the humpback whale has made a rapid recovery over the past four decades. The return of this apex predator, which has been functionally extinct from coastal ecosystems during the era of modern fisheries, will need to be factored into fisheries management decisions and research on trophic interactions (Heinz et al. in prep). Prince William Sound offers unparalleled opportunity to understand the importance of top down control in structuring marine communities and long-term monitoring will be crucial to understanding this changing ecosystem.

Recommendations

It is important to remember that this effort focused on whale predation on herring during the fall and winter months. Predation by whales on herring occurs throughout the year and is particularly intense during spawning. We have not assessed the impacts of whales during the spring and summer, thus, herring mortality due to whale predation may be significantly higher than we are presenting.

Recent surveys have identified a shift in the foraging behavior of humpback whales in PWS relative to the work presented here. It appears that humpback whales have switched from a diet dominated by adult herring, to increasing proportions of juvenile herring and euphausiids. It is not known if this represents a decrease in the availability of adult herring or an increase in the abundance of krill and juvenile herring. Perhaps adult herring have altered their behavior to avoid predation by whales. Sawmill Bay on Evans Island was a “Hot Spot” for overwintering herring, whales, sea lions, and birds, however, it now appears that the herring have abandoned the area, possibly as a response to heavy predation by whales. Anecdotal observations from our surveys suggest an increase in euphausiids abundance. A quantifiable assessment of prey and whale foraging strategies could provide valuable information on trophic interactions within the Sound.

Humpback whales are opportunistic predators capable of foraging on a variety of species across several trophic levels. Understanding and documenting their function in the ecosystem and how it varies over time may provide insight into the state of Gulf of Alaska ecosystem (Figure 2-10). We recommend a fine scale study of humpback whale diet and foraging strategies to identify trends from predation in forage fish and euphausiids populations. This would require bioacoustics tagging to reveal dive depth behavior and detailed acoustic surveys combined with ground-truthing. Stable isotopes and fatty acid should be incorporated to determine trophic relationships. Humpback whales sampled during the summer in PWS are known to be genetically and trophically distinct (Witteveen et al. 2009, 2011). We recommend further genetic analysis from samples collected throughout the year to determine if PWS humpback whales truly represent a unique feeding aggregation. This is important because humpback whales return as juveniles and adults to the feeding area where as a calf they were brought by their mothers. These feeding aggregations of humpback whales are genetically distinct because the mtDNA/haplotypes are inherited from the mother. Feeding behaviors and prey preferences appear to be culturally transmitted from whale to whale and especially from mother to offspring. Thus knowing if these whales are a genetically distinct feeding aggregation with prey preferences would impact a preferred prey species over another prey. This would be analogous to ecotypes in killer whales and knowing the preferential diet if fish or marine mammal is important understanding in top down pressure at an ecosystem level.

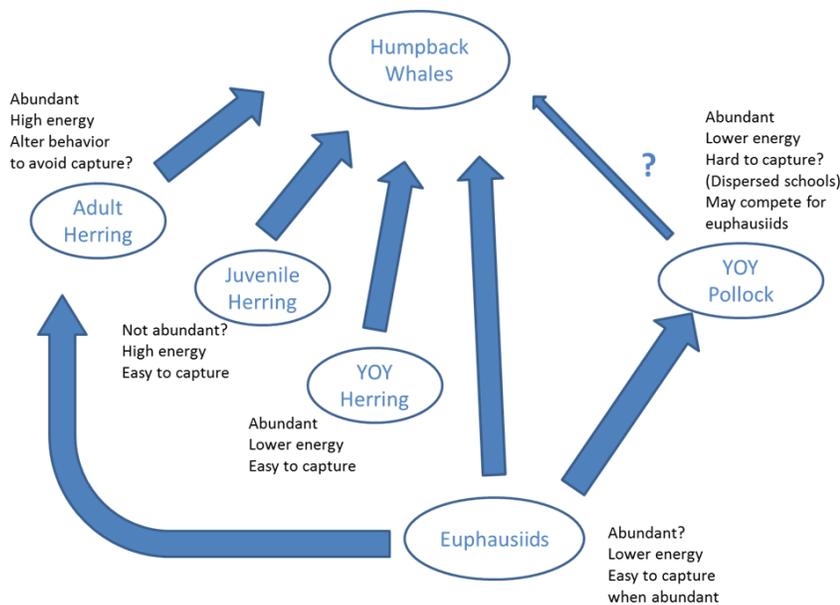


Figure 3-11 Conceptual model of humpback whale foraging options based on recent observations (July and Sept. of 2014) in Montague Strait and Port Gravina. Variation in humpback whale prey selection may be an indicator of changes at lower trophic levels.

References

- Acquarone, M., E. W. Born, and J. R. Speakman. 2006. Field Metabolic Rates of Walrus (*Odobenus rosmarus*) Measured by the Doubly Labeled Water Method. *Aquatic Mammals* 32:363–369.
- ADFG. 2010. Herring Fisheries in Alaska Catch, Effort and Value Information. Juneau: State of Alaska Herring Catch Statistics for the State, ADF&G website. Juneau, Alaska.
- ADFG. 2012. 2011 Alaska Commercial Herring Sac Roe Harvests & Exvessel Values, ADF&G website.
- Barlow, J., J. Calambokidis, E. A. Falcone, C. S. Baker, A. M. Burdin, P. J. Clapham, J. K. B. Ford, C. M. Gabriele, R. LeDuc, D. K. Mattila, T. J. Quinn, L. Rojas-Bracho, J. M. Straley, B. L. Taylor, J. Urbán R., P. Wade, D. Weller, B. H. Witteveen, and M. Yamaguchi. 2011. Humpback whale abundance in the North Pacific estimated by photographic capture-recapture with bias correction from simulation studies. *Marine Mammal Science* 27(4):793–818.
- Clapham, P. J., S. Childerhouse, N. J. Gales, L. Rojas-Bracho, M. F. Tillman, and R. L. Brownell. 2007. The whaling issue: Conservation, confusion, and casuistry. *Marine Policy* 31(3):314–319.
- Gerber, L. R., L. Morissette, K. Kaschner, and D. Pauly. 2009. Ecology. Should whales be culled to increase fishery yield? *Science* 323(5916):880–1.
- Leaper, R., and D. M. Lavigne. 2007. How much do large whales eat? *Journal of Cetacean Research Management* 9:179–188.
- Marty, G. D., P.-J. F. Hulson, S. E. Miller, T. J. Quinn, S. D. Moffitt, and R. a Merizon. 2010. Failure of population recovery in relation to disease in Pacific herring. *Diseases of aquatic organisms* 90(1):1–14.
- Morishita, J. 2006. Multiple analysis of the whaling issue: Understanding the dispute by a matrix. *Marine Policy* 30(6):802–808.
- Nichol, L., and K. Heise. 1992. The Historical Occurrence of Large Whales of the Queen Charlotte Islands. Page 67. South Moresby/Swaii Haanas National Park Reserve, British Columbia.
- Perez, M. A., and W. B. Mcalister. 1993. Estimates of Food Consumption by Marine Mammals in the Eastern Bering Sea. NOAA Technical Memorandum NMFS-AFSC-(May):36.
- Rice, S. D., and M. G. Carls. 2007. Prince William Sound Herring: An updated synthesis of population declines and lack of recovery. “Exxon Valdez” Oil Spill Restoration Project Final Report. National Marine Fisheries Service Juneau, Alaska.
- Sigler, M. F., and D. J. Csepp. 2007. Seasonal abundance of two important forage species in the North Pacific Ocean, Pacific herring and walleye pollock. *Fisheries Research* 83(2-3):319–331.

- Wahrenbrock, E. A., G. F. Maruschak, R. Elsner, and D. W. Kenney. 1974. Respiration and Metabolism in Two Baleen Whale Calves. *Marine Fisheries Review* 36:1–9.
- White, G. C., and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. *Bird Study* 46(sup001):S120–S139.
- Witteveen, B., J. Straley, E. Chenoweth, C. Baker, J. Barlow, C. Matkin, C. Gabriele, J. Neilson, D. Steel, O. von Ziegesar, A. Andrews, and a Hiron. 2011. Using movements, genetics and trophic ecology to differentiate inshore from offshore aggregations of humpback whales in the Gulf of Alaska. *Endangered Species Research* 14(3):217–225.
- Witteveen, B., G. Worthy, K. Wynne, and J. Roth. 2009. Population structure of North Pacific humpback whales on their feeding grounds revealed by stable carbon and nitrogen isotope ratios. *Marine Ecology Progress Series* 379:299–310.

FORAGE FISH POPULATIONS IN PRINCE WILLIAM SOUND: DESIGNING EFFICIENT MONITORING TECHNIQUES TO DETECT CHANGE

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Introduction

Forage species of Prince William Sound (PWS) are an important node in marine food webs of the Sound because they link primary and secondary producers with higher trophic levels. Forage species typically produce a large number of offspring and have short life spans, and these traits predispose populations to large fluctuations in abundance, with subsequent impacts on predators. Examples of important forage taxa in PWS include capelin (*Mallotus villosus*), Pacific sand lance (*Ammodytes hexapterus*), juvenile walleye pollock (*Theragra chalcogramma*), eulachon (*Thaleichthys pacificus*), Pacific herring (*Clupea pallasii*) and euphausiids (Euphausiacea), all included hereafter under the label of “forage fish”.

In 1999, the Fishery Management Plan for the Groundfish Fishery adopted amendments 36 and 39 for the Bering Sea/Aleutian Islands and Gulf of Alaska, respectively, that prohibited a directed commercial fishery on species known to be important (excluding Pacific herring and walleye pollock) for supporting healthy populations of higher trophic organisms such as marine mammals, seabirds, and commercially important fish. In contrast to commercial fish species that require regular stock assessments for management purposes, standardized methods for monitoring forage fish in Alaska are not well established in any region (Ormseth 2014). This is due in no small measure to the patchy distribution of schools, high mobility, and differing life histories among the various species of interest. In short, forage fish are notoriously difficult to study. Several different approaches have been employed in PWS and the Gulf of Alaska region in recent decades with varying degrees of success.

In response to a lack of recovery of wildlife populations following the *Exxon Valdez* Oil Spill (EVOS) (Peterson et al. 2003b), and evidence of natural background changes in forage fish abundance (Anderson and Piatt 1999), a significant effort was made to document forage fish distribution, abundance, and variability in PWS and Cook Inlet in the 1990’s (Thedinga et al. 2000, Brown 2002, Ainley et al. 2003, Abookire and Piatt 2005, Speckman et al. 2005, Piatt et al. 2007c). Survey methods for estimating abundance and distribution of forage fish included hydroacoustic surveys coupled with trawl-sampling (Haldorson et al. 1998, Speckman et al. 2005) and Sound-wide aerial surveys for surface-schooling fish (Brown and Moreland 2000). Aerial surveys were also repeated in 2010-2012 under the herring research and monitoring program.

A less traditional effort to document forage fish populations from predator diets in the South-central Alaska region was undertaken by the U.S. Geological Survey at Middleton Island, a colony near the continental shelf break about 100 km from the Hinchinbrook Entrance of PWS (Hatch 2013b). This work spanned the time period from 1978 – 2013 and provides an index of forage fish abundance and species composition in seabird diets. The Middleton forage fish index represents the longest continuous time series in the region. The use of predators as samplers of forage stocks as a complement to more traditional sampling methods that employ boats, nets and hydroacoustics is widely employed around the globe (Sinclair and Zeppelin 2002, Boldt 2005, Yang et al. 2005, Piatt et al. 2007a), and the ability of Middleton Island’s long-term dataset to demonstrate change in forage stocks is increasingly evident (Thayer et al. 2008, Hatch 2013b).

Since 2012, the forage fish component of the Gulf Watch Alaska program has been working to 1) identify robust methods for monitoring forage fish in PWS, 2) design a repeatable sampling strategy to measure forage fish distribution and abundance over time, and 3) relate forage fish distribution and abundance to habitat. Here we will detail methods and summarize relevant findings from previous and current efforts to document forage fish in the Sound and surrounding areas in south-central Alaska. We will also provide the scientific rationale for a survey design that combines technologies to maximize repeatability and minimize variance in forage fish estimates in the future.

Methods for Sampling Forage Fish in PWS

Historical methods for sampling forage fish in this region include coupled hydroacoustic-trawl surveys, aerial surveys, and sampling predator diets. Each method has advantages and limitations, which will be discussed below. We also discuss the aerial-acoustic design implemented in 2014 that will continue in 2015.

Hydroacoustic-trawl Surveys

Hydroacoustic detection and measurement of fish school signal strength is a common way to estimate fish biomass in the water column. Using this method, calibrated scientific echosounders emit a sound wave into the water at one or more frequencies, and integration of the returned echo signal strength can be translated into fish density and biomass when the species composition, size, and sound-scattering properties (or ‘target strength’) of the ensonified fish are known. The field of fisheries hydroacoustics has evolved dramatically in recent decades with more focused research on the back-scattering properties of fish, as well as advances in sonar and data processing technology. Still, back-scattering properties of fish and other organisms are variable under different biological and physical conditions, which makes it impossible to reliably identify individual species using returning target signals alone (Horne 2000). We still need expert knowledge of habitat and behavioral differences among species, as well as direct sampling with trawls (or other means of capture/identification) used in conjunction with multi-frequency echosounders in order to classify aggregations and estimate prey biomass.

Hydroacoustic-trawl surveys are used to aid in stock assessments and management of major commercial fisheries including the Peruvian anchovy (Simmonds et al. 2009), Atlantic herring (Overholtz et al. 2006), and Alaskan walleye pollock (Ianneli 2005). While the method is globally established, hydroacoustic estimation of fish biomass is hindered in shallow nearshore waters where most forage fish in PWS aggregate during summer. Hydroacoustic detection of fish schools is limited near the water’s surface and in nearshore waters because: 1) technical problems (transducer ringdown and near field range signal noise) usually require that we exclude detections closer than approximately 2 - 5 m at the frequencies typically employed (120 and 38 kHz, Simmonds and MacLennan 2005), 2) the cone-shaped beam pattern covers a narrower swath at shallower depths, 3) it is dangerous for all but the smallest vessels to survey in nearshore shallow waters (< 5-10 m bottom depth), and, 4) many fishes actively avoid boats under way. Furthermore, hydroacoustic-trawl surveys can be logistically prohibitive due to the high cost of equipment, software, expertise required to collect and analyze the data, and the need for a vessel large enough to accommodate a trawl-based fishing effort (a direct conflict with shallow-water based work nearshore).

Aerial Surveys

Aerial survey methods for estimating population size have been developed for many wildlife taxa including ungulates, marine mammals, and water fowl (e.g., Gasaway et al. 1986, Bodkin and Udevitz 1989, Quang and Lanctot 1991, Laake et al. 1997). Aerial surveys offer the advantage of surveying large areas quickly and at relatively low cost compared to ship-based surveys, but the method has obvious visibility limitations for assessing abundance of fish underwater. In an attempt to develop cost-effective survey methods for nearshore forage fish in PWS, Brown and others (e.g., Brown and Borstad 1998, Brown and Moreland 2000) initiated aerial surveys to document forage fish during the Alaska Predator Experiment (APEX) and Sound Ecosystem Assessment (SEA) projects in the late 1990's. These surveys were conducted from a fixed wing aircraft flying along the shoreline at altitudes of 275-365 m and speeds of 200 km/h. A sighting tube was used to estimate school size, and visual cues (distance from shore, school shape, color, etc.) were used to assign species to observations. On-the-ground validations of aerial observations in 1995-1997 occurred throughout the study period using nets, divers, or cameras. Of 6756 schools, 419 (6.2 %) were validated for species and size distribution. Aerial species misclassification rates were estimated at 6.8 and 20.2% for herring and sand lance, respectively (Norcross et al. 1999, Appendix VI).

Aerial surveys proved useful for documenting near-surface fish schools in nearshore areas where forage schools tend to aggregate in PWS during summer months (Brown and Moreland 2000). In contrast to vessel surveys, aerial surveys cover large areas quickly, but the precision and accuracy of aerial surveys are affected by variability in sighting conditions, water clarity, vertical distribution of fish in the water column, and observer bias (Norcross et al. 1999, Appendix VI). Furthermore, the combination of traveling at high speeds along a convoluted shoreline under rapidly changing viewing conditions makes density estimation from either strip or line transect surveys difficult. The assumption of complete detection within a narrow strip is hampered by the pilot's ability to stay on course a set distance from shore and the observer's ability to count and identify schools accurately. Line transect survey methods can remedy the issue of incomplete detection, but the detection function from line transects oriented parallel to shore is confounded by the school density gradient relative to the shoreline. In summary, PWS is well suited for aerial surveys of nearshore fish aggregations, but we are still left with uncertainties about species, age class, and density estimates, which can only be addressed by other means.

Predator Diets

Predator diets can provide quantitative information on abundance, distribution, temporal variability, condition and community structure of local prey stocks (Hatch and Sanger 1992, Davoren and Montevecchi 2003, Litzow et al. 2004). In the Gulf of Alaska, information on the diets of piscivorous seabirds, marine mammals, and predatory fish has been collected at breeding sites in the Gulf of Alaska and elsewhere (Piatt and Anderson 1996, Sinclair and Zeppelin 2002, Yang et al. 2005, Thayer et al. 2008).

Researchers may use a variety of methods to gather diet information about marine predators such as: collect prey remains in scat or regurgitations, sacrifice the animal to examine stomach contents, or in the case of some seabirds, collect whole fish intended for seabird chicks at the nest. The relative occurrence of species in such samples can be a cost effective index of prey availability. The collection of whole fish from chicks also affords advantages over the others because it is minimally invasive for the predator, and information about prey body condition (length, weight, energetics, etc.) can be gathered from whole fish

(in contrast to digested food items from stomachs or regurgitations). Drawbacks of using predators as indicators of forage fish stocks are the potential for prey selectivity among generalist vs. specialist predators, non-random sampling of foraging areas, and restrictions on the depth of sampled prey because of predator limitations (Hunt et al. 1991). For example, tufted puffins (*Fratercula cirrhata*) bring a greater diversity of prey items to their nest than the horned puffins (*F. corniculata*) (Hatch and Sanger 1992), suggesting the tufted puffin diets represent a more opportunistic sample of food availability than horned puffins. Some species, like surface-feeding kittiwakes, are limited in their diving depth and their diets are representative only of prey which make it to the surface at some point in their diurnal cycle of vertical migration (Hatch 2013b). Nonetheless, the advantages of easy access and sampling can outweigh the known sampling biases or disadvantages, and in the absence of traditional fisheries surveys for forage fish in the region, the information gleaned from predator diets at seabird colonies provides the best continuous long-term information available on some forage fish species in the northern Gulf of Alaska.

Overview of Gulf Watch Alaska Forage Fish Methods

During 2012-2013 field seasons we conducted fish, seabird, zooplankton, oceanography and nutrients sampling at 27 fixed stations using a stratified systematic design (Arimitsu and Piatt 2014). Hydroacoustics and midwater trawl composition at systematically-placed stations throughout PWS suggested our encounter rate with target species was not sufficient to assess abundance. Frequency of occurrence in trawls (FO) was low for capelin (3.7%), eulachon (3.7%), and euphausiids (11.1%), and catches were overwhelmingly dominated by non-target species (young of the year walleye pollock, FO = 100%, and jelly fish FO = 81.5%). Likewise, beach seines targeting Pacific sand lance had low and variable catches (mean CPUE \pm SD = 3.5 ± 10.5 fish per set). Thus we explored ways to improve our ability to sample target fish species.

In 2013 we explored the use of adaptive cluster sampling for at-sea surveys, and tested whether we could use aerial surveys to locate nearshore schools of fish, and then use acoustic/trawl surveys to validate our aerial observations and collect specimens for other purposes as well. Our goal of combining aerial and ship-based methods (hereafter called “aerial-acoustic surveys”) was to markedly increase our encounter rate with target species and increase our acoustic/trawl sampling rates of target species at sea.

Results of aerial-acoustic survey trials in 2013 were mixed. Adaptive cluster sampling (i.e., intensive sampling around schools we found during surveys or by chance) generally involved a high degree of effort and did not facilitate a quantitative means of assessing abundance and distribution at the sound-wide scale. We also devoted three days of ship time to validation of aerial surveys. An experienced spotting pilot directed the ship or a skiff to forage fish schools visible from the plane. Schools were captured with nets, jigs, video, and hydroacoustics whenever possible. The ground crew recorded, and relayed to the pilot, information about fish species, fish size, and depth of the schools. After the pilot left, we conducted hydroacoustic surveys of the area, and we used midwater trawls, gill nets, cast nets, dip nets, jigs, or video to confirm the species composition and fish size for conversion of acoustic backscatter to biomass. In 2014 we developed a new survey design that combined aerial and hydroacoustic survey methods again, but with refinements of sampling strategy (see below).

Combining Technologies: Aerial-Acoustic Survey Design

As a result of the disparity between separate aerial and acoustic survey efforts in PWS, Brown and Moreland (2000) described a need to combine the two survey methods because neither method adequately sampled forage fish schools alone.

Historical aerial survey methods established during the APEX and SEA projects in the late 1990's (Brown and Borstad 1998, Brown and Moreland 2000) serve as the statistical basis for the new survey design that was tested in 2014 and will continue in summer 2015. Shoreline aerial survey data from July 2010 – 2012 (Evelyn Brown, Flying Fish Ltd., Cordova, unpublished data) were analyzed to identify low, medium and high school density regions within the Sound (Figure 3-12). A 5' latitude by 5' longitude grid was overlaid on previous aerial track lines and observations in GIS. An index of school density was calculated for each grid cell such that the total number of schools observed was standardized by effort (length of aerial survey flown in km) and weighted by persistence (number of years schools were observed). Grid cells from high, medium and low density strata were randomly selected for sampling. The optimum sample size in each stratum was chosen to minimize variance of the population mean (Cochran 1977). Near-surface schools in each sampling block were censused by an experienced spotter pilot, and species composition and size of schools were assessed by a fisheries team working from a vessel. Vertical distribution of biomass by species was measured using hydroacoustic transects in a random subset (n = 15) of navigable blocks in the high-density stratum. The hydroacoustic surveys aimed to estimate the proportion of forage fish biomass below the surface that the aerial surveys are unable to sample. Where aerial and acoustic surveys overlap, an index of forage fish availability (aerial school density and acoustically determined biomass) will be compared among regions. The newly redesigned aerial-acoustic survey design aims to increase repeatability compared to the previous design, simplify the data collection and processing effort, and increase certainty in the species composition and school density index derived from aerial observations.

Predator Diets

Although we did not collect predator diets ourselves, we note that diets of several species of seabirds (including kittiwake, tufted puffin, and rhinoceros auklet (*Cerorhinca monocerata*)) were monitored on Middleton during the course of our studies (2012-2014), and time series for diets of some species extend back to the 1980s (Hatch 2013; S. Hatch, Institute for Seabird Research and Conservation, Anchorage, unpubl. data). A similar approach in sampling predator diets to monitor prey within PWS has been used in the past for tufted puffins (Piatt et al. 1998), kittiwakes (e.g., Jodice et al. 2009) and pigeon guillemots (e.g., Oakley and Kuletz 1996, Golet et al. 2000). Depending on the status of these species in PWS today (e.g., puffins appear to have declined owing to predation by mink), we believe that systematic sampling of avian forage fish predators has high potential for complementing aerial-acoustic monitoring of forage species in PWS and the Gulf of Alaska.

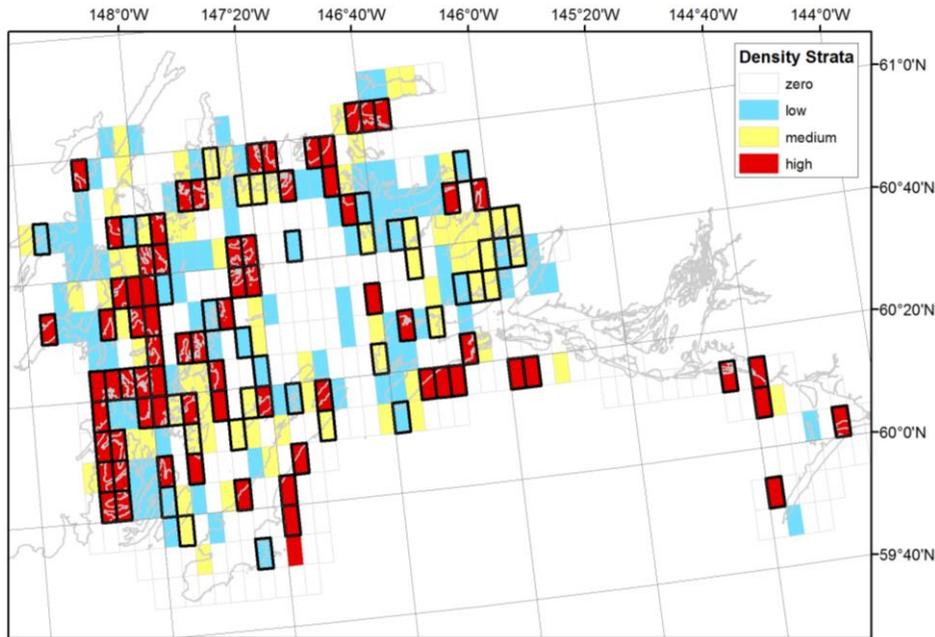


Figure 3-12. Density strata showing the distribution of forage fish schools (number of schools/km flown weighted by persistence over time) during July shoreline aerial survey counts from 2010-2012 (E. Brown, unpublished data). Forage fish aerial survey sampling blocks (outlined in bold) were selected to be sampled in the Gulf Watch Alaska program's forage fish monitoring component based on variability within low, medium, and high density strata.

Forage Fish Distribution and Abundance in PWS

A somewhat patchy effort has been devoted to explain forage fish distribution and availability in south-central Alaska in the past. Here we summarize species-specific results from these studies.

Capelin

Capelin are distributed in the Sound in the outer bays and exposed beaches in the southwest, north, Montague and Hinchinbrook Island during late spring and summer (Figure 3-13 this study, Brown et al. 2002, Brown 2002). Capelin are also associated with near surface euphausiids in cool turbid waters near tidewater glaciers in PWS and elsewhere (Arimitsu et al. 2008, Arimitsu and Piatt, in prep). Spawning was reported to occur on exposed beaches of Montague and Erlington Islands, and the head of Day Harbor (Brown et al. 2002) and at Port Etches (USGS, unpublished data). Large, irregularly-shaped schools of adult capelin were observed during June-August aerial surveys (Brown 2002). Larval capelin abundance peaks in July, which suggests major spawning events occur in June. Unlike other areas of Alaska (e.g., Kodiak and Glacier Bay, Pahlke 1985, Arimitsu et al. 2008) prolonged spawning does not appear to occur in PWS (Brown 2002). Although capelin were only occasionally encountered during the APEX work in PWS (Haldorson et al. 1998, Thedinga et al. 2000), in lower Cook Inlet, Capelin occurred more frequently in trawl catches and they increased in abundance between 1996 and 1999 (Abookire and

Piatt 2005). Capelin in Middleton Island kittiwake diets showed marked increases during recent cool years from 2000-2003, and 2008-2011 (Figure 3-14, Hatch 2013, Ormseth 2014).

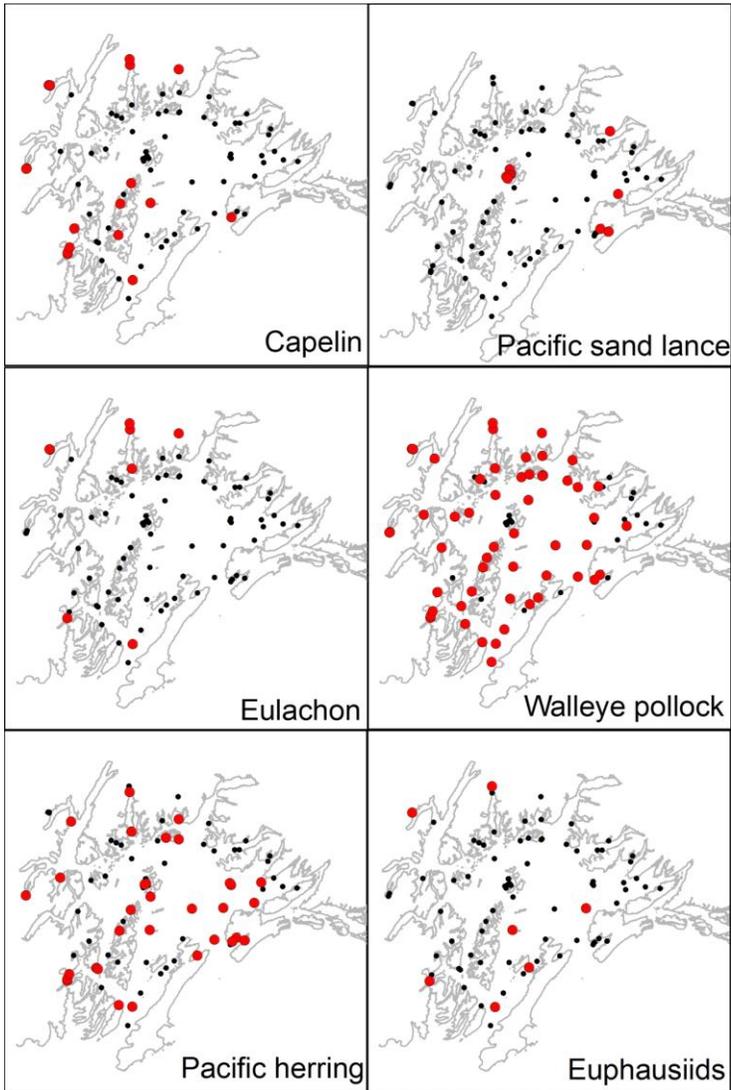


Figure 3-13. Distribution of fishing effort (including midwater trawl, beach seine, jig, purse seine and camera; black circles) and locations where forage fish were observed (red circles) during Gulf Watch Alaska project in summers of 2012-2014.

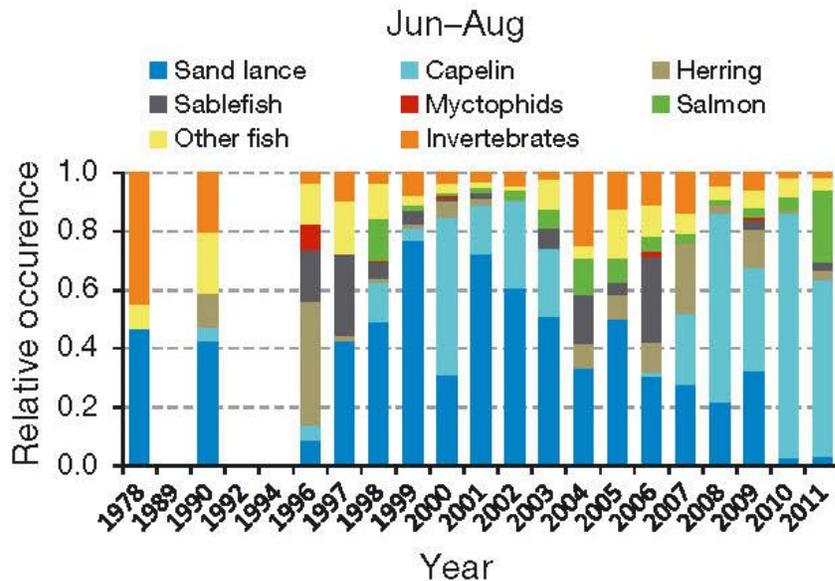


Figure 3-14. Black-legged kittiwake diet composition over time at Middleton Island, figure from Hatch (2013).

Pacific sand lance

Pacific sand lance are associated with shallow depths and sandy substrates (Robards et al. 1999, Ostrand et al. 2005). They spawn on intertidal substrates well after water temperatures cool again from late September to December primarily at age 1 – 3 (Robards 1999). They may be found burrowed in the sand or swimming in schools within the water column. Pacific sand lance abundance in aerial surveys peaked in 1997 and remained high through 1999 (Brown and Moreland 2000). Although Pacific sand lance made up just 0.5% of the acoustic biomass estimates from the APEX years, relative abundance was greatest in the northern region of PWS during 1999 (Thedinga et al. 2000). In 2012-14 we observed aggregations of Pacific sand lance near Naked Island and over Middle Ground Shoal (Figure 3-13). In lower Cook Inlet, Pacific sand lance were the most abundant forage fish in trawl catches and their numbers increased between 1996 – 1999 (Abookire and Piatt 2005). Near Middleton Island, greater occurrence of Pacific sand lance in diets occurred in 2004, 2006 and 2009, and Pacific sand lance and capelin percent composition in kittiwake diets were negatively correlated over time (Figure 3-14, Hatch 2013).

Juvenile Walleye Pollock

In summer juvenile walleye pollock are densely aggregated within bays (Stokesbury et al. 2000) and associated with jellyfish in small numbers throughout the upper water column and dispersed throughout the Sound (Purcell et al. 2000). Age-0 walleye pollock dominated midwater trawl catches throughout the Sound in 2012-14 (Figure 3-13), and the large aggregations of young of the year fish were encountered in Herring Bay and near Glacier Island. Large aggregations of age 1-2 pollock co-occurred with age 2+

herring near Knowles Head and Glacier Island during hydroacoustic surveys in 2013. Adult pollock aggregate near the bottom in deep waters throughout the Sound, and they are caught in trawls with capelin and euphausiids near tidewater glaciers.

Eulachon

Eulachon spawn in the Copper River Delta during spring, and they occur in marine waters near the outer passes in the southwest Sound, and off the southern tip of Montague Island (Brown et al 2002). Catch per unit effort from small-mesh trawl surveys in the Gulf of Alaska was below the long-term average in 2011-12 (Zador 2013). We observed juvenile and adult eulachon associated with near-surface aggregations of euphausiids and other dispersed forage fish near tidewater glaciers (Figure 3-13).

Pacific herring

Pacific herring are the focus of a much larger study, which this project is also in close collaboration with, to investigate the reason for the lack of recovery since the early 1990's. Thus the species is discussed in greater detail elsewhere. Along with walleye pollock, Pacific herring were the most frequently encountered species during work in summers of 2012 – 2014 (Figure 3-13). They were also a regular part of seabird diets at Middleton Island, especially during the latter half of the 2000s (Hatch 2013b).

Euphausiids

In the Gulf of Alaska, species specific changes in abundance of euphausiids occurred between 1998 and 2003. *Thysanoessa inermis* increased in abundance from 1998 to 2002, and declined in 2003, and *Euphausia pacifica* declined between 1998 and 2001 then increased from 2001 to 2003 (Pinchuk et al. 2008, Wilson et al. 2009). We encountered five species of euphausiids in PWS, including *E. pacifica*, *Thysanoessa spinifera*, *T. inermis*, *T. rashi*, and *T. longipes*. The presence of spermatophores in *T. spinifera* indicated spawning in July within glacial fjords.

Summary/Recommendations

In this synthesis we summarized several coordinated efforts to document the distribution and abundance of forage fish in PWS and surrounding areas over the past two decades. Due to differing life histories of multiple species with clustered distributions and highly variable populations, forage fish are notoriously difficult to study. Sampling methods include hydroacoustic-trawl surveys, aerial surveys of near-surface schooling fish, and the use of predator diets as indicators of forage fish abundance over time. A monitoring program that includes a variety of methods will improve our ability to document change over time. In PWS we are testing an improved forage fish survey design that combines aerial and hydroacoustic surveys. Due to the relative ease and efficiency that a predator diet component can provide (see Hatch 2013), addition of predator diet studies could further strengthen this aspect of the Gulf Watch monitoring program. Continued monitoring will be critical to understanding the role of natural and anthropogenic factors on forage fish populations in the region, and provide important information about the role forage fish play in the ecosystem.

References

Abookire, A. A., and J. F. Piatt. 2005. Oceanographic conditions structure forage fishes into lipid-rich and lipid-poor communities in lower Cook Inlet, Alaska, USA. *Marine Ecology Progress Series* 287:229–240.

- Ainley, D. G., R. G. Ford, E. D. Brown, R. M. Suryan, and D. B. Irons. 2003. Prey resources, competition, and geographic structure of kittiwake colonies in PWS. *Ecology* 84(3):709–723.
- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Marine Ecology Progress Series* 189:117–123.
- Arimitsu, M. L., J. F. Piatt, M. a. Litzow, A. A. Abookire, M. D. Romano, and M. D. Robards. 2008. Distribution and spawning dynamics of capelin (*Mallotus villosus*) in Glacier Bay, Alaska: a cold water refugium. *Fisheries Oceanography* 17(2):137–146.
- Boldt, J. (ed). 2005. Ecosystem Considerations 2005, Stock Assessment and Fishery Evaluation Report. Diversity. 605 W 4th Ave, Suite 306, Anchorage AK 99501.
- Brown, E. D. 2002. Life history, distribution, and size structure of Pacific capelin in PWS and the northern Gulf of Alaska. *ICES Journal of Marine Science* 59(5):983–996.
- Brown, E. D., and G. A. Borstad. 1998. Progress report on aerial survey development. Pages 10–61 – 10–101 in R. T. Cooney, editor. SEA97: Sound Ecosystem Assessment- An Integrated Science plan for the Restoration of Injured Species in PWS, Alaska.
- Brown, E. D., and S. M. Moreland. 2000. Ecological factors affecting the distribution and abundance of forage fish in PWS, Alaska: An APEX synthesis product. Project 00163T. Synthesis.
- Brown, E. D., J. Seitz, B. L. Norcross, and H. P. Huntington. 2002. Ecology of Herring and Other Forage Fish as Recorded by Resource Users of PWS and the Outer Kenai Peninsula , Alaska. *Alaska Fishery Research Bulletin* 9(2):73–104.
- Carscadden, J. E., B. Nakashima, and D. S. Miller. 1994. An Evaluation of Trends in Abundance of Capelin (*Mallotus villosus*) from Acoustics , Aerial Surveys and Catch Rates in NAFO Division 3L , 1982 – 89. *Journal of Northwest Atlantic Fishery Science* 17:45–57.
- Cochran, W. G. 1977. *Sampling Techniques*. John Wiley and Sons, New York.
- Davoren, G. K., and W. Montevecchi. 2003. Signals from seabirds indicate changing biology of capelin stocks. *Marine Ecology Progress Series* 258:253–261.
- Gasaway, W., S. DuBois, D. Reed, and S. Harbo. 1986. Estimating moose population parameters from aerial surveys. *Biological Papers of the University of Alaska* 22:1–125.
- Haldorson, L. H., T. C. Shirley, and K. O. Coyle. 1998. *Forage Species Studies in PWS*.
- Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. *Marine Ecology Progress Series* 477:271–284.

- Hatch, S. A., and G. A. Sanger. 1992. Puffins as samplers of juvenile pollock and other forage fish in the Gulf of Alaska. *Marine Ecology Progress Series* 80:1–14.
- Horne, J. K. 2000. Acoustic approaches to remote species identification : a review. *Fisheries Oceanography* 9(4):356–371.
- Hunt, G. L. J., J. F. Piatt, and K. E. Erikstad. 1991. How do foraging seabirds sample their environment? Pages 2272–2279 *Proceedings of the 20th International Ornithological Congress, 2-9 Dec. 1990. Christchurch, New Zealand.*
- Ianelli, J. 2005. Assessment and fisheries management of eastern Bering Sea walleye pollock: is sustainability luck? *Bulletin of Marine Science* 76(2):321–335.
- Laake, J. L., J. Calambokidis, S. D. Osmek, and D. J. Rugh. 1997. Probability of Detecting Harbor Porpoise from Aerial Surveys : Estimating $g(0)$. *Journal of Wildlife Management* 61(1):63–75.
- Litzow, M. a., J. F. Piatt, A. a. Abookire, and M. D. Robards. 2004. Energy density and variability in abundance of pigeon guillemot prey: support for the quality-variability trade-off hypothesis. *Journal of Animal Ecology* 73(6):1149–1156.
- Norcross, B. L., E. D. Brown, R. J. Foy, M. Frandsen, J. Seitz, and K. D. E. Stokesbury. 1999. Juvenile herring growth and habitats, Exxon Valdez Oil Spill Restoration Project Final Report. Restoration Project 99320T.
- Ormeth, O.A. 2014. Gulf of Alaska Forage Fishes. In: Stock Assessment and Fishery Evaluation Report for the Gulf of Alaska. North Pacific Fisheries Management Council, 605 W. 4th Ave, Ste 306, Anchorage AK 99501.
- Ostrand, W. D., T. A. Gotthardt, S. Howlin, and M. D. Robards. 2005. Habitat Selection Models for Pacific Sand Lance (*Ammodytes Hexapterus*) in PWS, Alaska. *Northwestern Naturalist* 86(3):131–143.
- Overholtz, W. J., J. M. Jech, W. L. Michaels, L. D. Jacobson, and P. J. Sullivan. 2006. Empirical comparisons of survey designs in acoustic surveys of Gulf of Maine-Georges Bank Atlantic herring. *Journal of Northwest Atlantic Fishery Science* 36:127–144.
- Pahlke, K. A. 1985. Preliminary studies of capelin (*Mallotus villosus*) in Alaskan waters. Informational Leaflet No. 250, Alaska Department of Fish and Game.
- Peterson, C. H., S. D. Rice, J. W. Short, D. Esler, J. L. Bodkin, B. E. Ballachey, and D. B. Irons. 2003. Long-term ecosystem response to the Exxon Valdez oil spill. *Science* 302(5653):2082–2086.
- Piatt, J. F., and P. J. Anderson. 1996. Response of common murrelets to the Exxon Valdez oil spill and long-term changes in the Gulf of Alaska marine ecosystem. *American Fisheries Society Symposium* 18:720–737.

- Piatt, J. F., A. Harding, M. Shultz, S. G. Speckman, T. van Pelt, G. S. Drew, and A. Kettle. 2007a. Seabirds as indicators of marine food supplies: Cairns revisited. *Marine Ecology Progress Series* 352(1987):221–234.
- Piatt, J. F., W. J. Sydeman, and F. Wiese. 2007b. Introduction: a modern role for seabirds as indicators. *Marine Ecology Progress Series* 352:199–204.
- Pinchuk, A. I., K. O. Coyle, and R. Hopcroft. 2008. Climate-related variability in abundance and reproduction of euphausiids in the northern Gulf of Alaska in 1998–2003 ☆. *Progress In Oceanography* 77(2-3):203–216.
- Purcell, J. E., E. D. Brown, K. D. E. Stokesbury, L. H. Haldorson, and T. C. Shirley. 2000. Aggregations of the jellyfish *Aurelia labiata*: abundance, distribution, association with age-0 walleye pollock, and behaviors promoting aggregation in PWS, Alaska, USA. *Marine Ecology Progress Series* 195:145–158.
- Quang, P. X., and R. B. Lanctot. 1991. A Line Transect Model for Aerial Surveys. *Biometrics* 47(3):1089–1102.
- Robards, M. D. 1999. Maturation, fecundity, and intertidal spawning of Pacific sand lance in the northern Gulf of Alaska. *Journal of Fish Biology* 54(5):1050–1068.
- Robards, M. D., M. F. Willson, and R. H. Armstrong. 1999. Sand Lance : A Review of Biology and Predator Relations and Annotated Bibliography. Page 327. Portland, OR.
- Simmonds, E., M. Gutierrez, A. Chipollini, F. Gerlotto, M. Woillez, and A. Bertrand. 2009. Optimizing the design of acoustic surveys of Peruvian anchoveta. *ICES journal of Marine Science* 66:1341–1348.
- Simmonds, E., and D. MacLennan. 2005. *Fisheries Acoustics: Theory and Practice*, Second Edition. Blackwell Science, Ames, Iowa.
- Sinclair, E. H., and T. K. Zeppelin. 2002. Seasonal and Spatial Differences in Diet in the Western Stock of Steller Sea Lions (*Eumetopias jubatus*). *Journal of Mammalogy* 83(4):973–990.
- Speckman, S. G., J. F. Piatt, C. Mintevera, and J. Parrish. 2005. Parallel structure among environmental gradients and three trophic levels in a subarctic estuary. *Progress In Oceanography* 66(1):25–65.
- Stokesbury, K. D. E., J. Kirsch, E. D. Brown, G. L. Thomas, and B. L. Norcross. 2000. Spatial distributions of Pacific herring, *Clupea pallasii*, and walleye pollock, *Theragra chalcogramma*, in PWS, Alaska. *Fishery Bulletin* 98:400–409.
- Thayer, J. a., D. F. Bertram, S. A. Hatch, M. J. Hipfner, L. Slater, W. J. Sydeman, and Y. Watanuki. 2008. Forage fish of the Pacific Rim as revealed by diet of a piscivorous seabird: synchrony and

relationships with sea surface temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 65(8):1610–1622.

Thedinga, J. F., L. B. Hulbert, and K. O. Coyle. 2000, March. Abundance and distribution of forage fishes in PWS. Alaska predator ecosystem experiment in PWS and the Gulf of Alaska. Exxon Valdez Trustee Council Restoration Project 00163A Final Report, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Auke Bay Laboratory, Juneau, Alaska.

Wilson, M., C. Jump, and a Buchheister. 2009. Ecology of small neritic fishes in the western Gulf of Alaska. II. Consumption of krill in relation to krill standing stock and the physical environment. *Marine Ecology Progress Series* 392:239–251.

Yang, M., K. Y. Aydin, A. Greig, G. Lang, and P. Livingston. 2005. Historical Review of Capelin (*Mallotus villosus*) Consumption in the Gulf of Alaska and Eastern Bering Sea. NOAA Technical Memorandum NMFS-AFSC-155.

Zador, S. G. (ed). 2013. Ecosystem Considerations 2013, Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage AK 99501.

SPATIAL AND TEMPORAL VARIATION IN MARINE BIRDS IN THE NORTHERN GULF OF ALASKA: THE VALUE OF MARINE BIRD MONITORING WITHIN GULF WATCH ALASKA

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Introduction

Birds offer useful insights into marine ecosystems. Marine birds are responsive to spatial and temporal variation in the environment, that often originates with fluctuations in oceanographic and climatic drivers and permeates up through food webs to conspicuous top predators such as seabirds (Coyle and Pinchuk 2005, Speckman et al. 2005, Gonzales-Solis et al. 2009, Cushing et al., this report). In that way, marine birds are excellent assimilators, samplers, and indicators of the status of marine environments (Montevecchi 1993, Piatt et al. 2007b, Zador et al. 2013). Marine bird responses to dynamic marine ecosystems can be detected in a variety of metrics, including abundance, distribution, and productivity. For example, in the northern Gulf of Alaska (GOA), decadal-scale variation in oceanographic conditions has been associated with dramatic shifts in prey composition and abundance (Anderson and Piatt 1999). In turn, these shifts were more closely correlated with changes in abundance of fish-eating birds of Prince William Sound (PWS), such as pigeon guillemots (Golet et al. 2002) and marbled and Kittlitz's murrelets (Kuletz et al. 2011a, 2011b), than in the abundance of species that primarily consume plankton or benthic prey (Agler et al. 1999, Cushing et al., this report).

Birds also are responsive to anthropogenic influences in marine environments, including commercial fishing, contamination, introduction of non-native species, coastal development, offshore resource extraction, and vessel traffic. A major anthropogenic perturbation in the northern GOA was the 1989 *Exxon Valdez* oil spill, in which marine birds suffered high immediate mortality (Piatt and Ford 1996). Additionally, several species showed long-term evidence of declines in the oiled areas of PWS (Lance et al. 2001), as well as impacts to reproductive success years later (Golet et al. 2002). However, the degree of direct impact and vulnerability to chronic injury, which was related to exposure to lingering oil, varied widely among species (see Esler et al., this report). Research and monitoring directed at documenting the timelines and mechanisms of wildlife recovery following the *Exxon Valdez* oil spill led to an unprecedented understanding of oil spill effects on marine birds, as well as previously unknown information about marine bird ecology in the northern GOA. Quantifying effects of anthropogenic influences requires an understanding of variation in marine bird abundance, distribution, and productivity, in relation to naturally occurring dynamics in marine environments continued marine bird work as part of Gulf Watch Alaska will facilitate this.

In addition to their value as indicators of marine conditions and anthropogenic influences, marine birds are protected under the Migratory Bird Treaty Act and are managed by the U.S. Fish and Wildlife Service (USFWS). Marine birds have high societal value from a wide variety of interests (e.g., tourism, bird watching, hunting, mythology), and are an important source of subsistence foods in Alaska (Naves and Braem 2014). Because of the conservation interest in marine birds, as well as their value for indicating the status of marine ecosystems, monitoring of marine birds is an important component of many ocean monitoring programs, including Gulf Watch Alaska.

Birds of the Northern Gulf of Alaska

The marine bird community in the area considered under Gulf Watch Alaska is typical of the North Pacific, in general. As an example, in PWS between 1989 and 2007 (McKnight et al. 2008), numbers of marine birds averaged roughly 250,000 in both summer and winter (see also Cushing et al., this report). Marine bird community composition varied considerably between seasons. In summer, numbers are dominated by species that are traditionally considered to be seabirds, including pigeon guillemots, marbled murrelets, tufted puffins, fork-tailed storm petrels, glaucous-winged gulls, and black-legged kittiwakes. In winter, seabirds still predominate, in particular seabirds that occur all year such as gulls, marbled murrelets, and species like common murre that move into PWS from outer coast breeding areas (Dawson et al. *in press*, Piatt and Van Pelt 1997). However, in contrast to summer, winter waterfowl numbers increase dramatically in PWS, particularly sea ducks such as Barrow's goldeneyes, harlequin ducks, mergansers, and scoters. Migration brings pulses of many species through the northern GOA, although numbers and species composition tend to be variable and generally poorly documented outside of summer.

The marine birds of the northern GOA can be generally divided into “pelagic” and “benthic” groups, based on their diet and primary foraging habitat. Pelagic species are those that consume forage fish or zooplankton (including euphausiids) in the water column, and thus are top predators in the food web originating from phytoplankton, to zooplankton, to forage fish. These tend to be the “traditional” seabirds, and are abundant during summer, and for some species, during winter as well. Benthic marine bird species are predators that consume bivalves or other benthic invertebrates, and are apex predators in trophic systems that originate with primary production from both phytoplankton and nearshore macroalgae such as kelp. Benthic marine bird species are numerically dominated by waterfowl, which are more abundant in PWS during winter. In general, pelagic bird distributions tend to be farther offshore than are benthic birds. Indeed, recent analyses indicate that marine bird community composition in PWS is strongly related to distance from shore and water depth (Cushing et al., this report), although in winter, the distribution of some pelagic species are also influenced by exposure to wave action and sea surface salinity (Dawson et al. *in press*).

Historical and Ongoing Marine Bird Monitoring in the Northern Gulf of Alaska

A variety of marine bird monitoring efforts have been conducted in the north GOA. A list of marine bird monitoring activities has been compiled and summarized (see Chapter 2, Appendix 1, page 3—79 of this report), to indicate the temporal and spatial coverage of studies, the intent (e.g., quantification of distribution, abundance, and/or productivity), and whether they are ongoing. In general, many of these have been of limited duration or geographic scope. However, there are some data sets that warrant mention for their value for understanding long-term and/or broad-scale status and trends of marine birds. In particular, surveys conducted by the USFWS, funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) and now part of Gulf Watch Alaska, have provided estimates of abundance and distribution of marine birds in PWS in summer and winter since 1989 (McKnight et al. 2008, Lance et al. 2001, Cushing et al., *this report*). Summer surveys are scheduled to continue as part of ongoing Gulf Watch efforts, although USFWS winter surveys have been discontinued since 2010.

Several Gulf Watch Alaska studies examine relative abundance and distribution of marine birds on a more temporally or spatially limited basis, using ships of opportunity; these are: 1) the PWS Science Center surveys (2007 to present) conducted from October through March (Dawson et al., *in press*, Stocking et al., *this report*); 2) seabird surveys in conjunction with the seventeen-year Seward Line/ GAK

1 oceanographic and zooplankton surveys (May and September) that were done sporadically and became a permanent component of the project in 2014; and 3) seabird surveys in conjunction with the Lower Cook Inlet oceanographic surveys (4 times annually since 2012). These types of surveys can provide data on spatial distribution over time, but not population estimates. The Gulf Watch Benthic component also includes intermittent winter surveys in Kenai Fjords and Katmai National Parks (see Coletti and Wilson, *this report*). One project not funded as part of Gulf Watch that collects winter data on marine birds is the monthly Resurrection Bay surveys conducted by Alaska Sea Life Center (2011 to present).

Counts of nesting birds and colony-based indices of seabird productivity in the northern GOA were conducted during the decade or so after the 1989 oil spill (Golet et al. 2002, Piatt 2002, Suryan et al. 2002, Litzow and Piatt 2003), but today such work is only regularly conducted at about 6 breeding sites. The USFWS Alaska Maritime National Wildlife Refuge monitors colonially nesting seabirds at 4 sites in the northern GOA on a rotating basis (Dragoo et al. 2013). Additionally, USFWS conducts counts of nesting kittiwakes in PWS and a long-term monitoring project was conducted by USGS until 2012 at Middleton Island (continued through the Institute for Seabird Research and Conservation). None of these are part of Gulf Watch Alaska program. The pigeon guillemot restoration project, funded by EVOSTC but not part of Gulf Watch Alaska, has a productivity component to track recovery of this injured species in conjunction with invasive mink removal; it will monitor pigeon guillemot productivity and diet from 2015 - 2018. Currently, two programs explicitly quantify marine bird productivity of nearshore species; these are: 1) the Gulf Watch Alaska Benthic component monitors black oystercatcher productivity at several areas of the GOA, and 2) marine bird monitoring in Resurrection Bay includes age class determination of sea ducks, as an indicator of productivity (Iverson et al. 2003).

Marine Bird Monitoring Challenges

Given the variety of species, habitats, and seasons requiring consideration when designing monitoring studies of marine birds in the northern GOA, no single monitoring activity is appropriate for comprehensively quantifying abundance, distribution, and productivity of all species. For non-colonial seabirds (e.g., *Brachyramphus* murrelets), population trends must be monitored by at-sea surveys, but a species' pattern of distribution can affect our ability to detect trends. For example, detecting trends for Kittlitz's murrelet is challenging because they are uncommon and highly clumped (Kuletz et al. 2011a).

Little is known about marine birds in the GOA during non-breeding periods of the annual cycle, in part because of the remoteness of the region and the inclement weather outside of summer. However, as noted above, total marine bird abundance in PWS is similar between breeding and non-breeding seasons, although the species composition, distribution patterns, and prey base change considerably (Bishop and Kuletz, *this report*, Dawson et al. *in press*, Hunt et al. 2005, McKnight et al. 2008). Indeed, in an expanded area of the northern GOA, estimated prey biomass consumption by marine birds in winter exceeded that of summer, due largely to the influx of overwintering sea ducks (Hunt et al. 2005). Obviously, a full understanding of the ecosystem requires a better understanding of the non-breeding period. In addition, for pelagic species, surveys conducted from November through March have found that species composition and abundance does not simply shift in fall and spring – rather they change throughout the year (see Bishop et al., *this report*). The definition of 'winter' for marine birds thus will depend on the focal species of interest and practical aspects of conducting monitoring activities in remote locations.

In addition to documenting changes in abundance and distribution, measures of productivity are useful for understanding mechanisms by which variation in ocean conditions leads to changes in marine bird populations. For colonially-nesting species such as black-legged kittiwakes (Piatt et al. 2002, Suryan et al. 2002) or pigeon guillemots (Golet et al. 2000, Litzow and Piatt 2003), it is possible to directly document changes in diet, chick growth, and reproductive success. Due to the expense and time required to collect these data, however, they are not often incorporated into long-term monitoring. Some situations, such as colonies on Middleton Island, allow easier access to seabirds to collect diet and productivity data (Hatch 2013a).

References

- Agler, B. A., S. J. Kendall, D. B. Irons, and S. P. Klosiewski. 1999. Declines in marine bird populations in Prince William Sound, Alaska coincident with a climatic regime shift. *Waterbirds* 22(1):98–103.
- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Marine Ecology Progress Series* 189:117–123.
- Coyle, K. O., and A. I. Pinchuk. 2005. Seasonal cross-shelf distribution of major zooplankton taxa on the northern Gulf of Alaska shelf relative to water mass properties, species depth preferences and vertical migration behavior. *Deep Sea Research Part II: Topical Studies in Oceanography* 52(1-2):217–245.
- Dawson, N. M., M. A. Bishop, K. J. Kuletz, and A. F. Zuur. *In press*. Using ships of opportunity to assess winter habitat associations of seabirds in subarctic coastal Alaska. Northwest Science.
- Dragoo, D. E., H. M. Renner, and Iron. 2013. Breeding status and population trends and diets of seabirds in Alaska, 2009. U.S. Fish and Wildlife Service Report AMNWR 2012/01. Homer, AK.
- Golet, G. H., K. J. Kuletz, D. D. Roby, and D. B. Irons. 2000. Adult prey choice affects chick growth and reproductive success in pigeon guillemots. *Auk* 117:82.
- Golet, G. H., P. E. Seiser, A. D. McGuire, D. D. Roby, J. B. Fischer, K. J. Kuletz, D. B. Irons, T. A. Dean, and S. C. Jewett. 2002. Long-term direct and indirect effects of the “Exxon Valdez” oil spill on pigeon guillemots in Prince William Sound, Alaska. *Marine Ecology Progress Series* 241:287–304.
- Gonzales-Solis, J., K. J. Kuletz, and S. A. Shaffer. 2009. Introduction and synthesis: spatial ecology of seabirds at sea. *Marine Ecology Progress Series* 391:117–120.
- Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. *Marine Ecology Progress Series* 477:271–284.
- Hunt, G. L., G. S. Drew, J. Jahncke, and J. F. Piatt. 2005. Prey consumption and energy transfer by marine birds in the Gulf of Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography* 52(5-6):781–797.
- Iverson, S. A., D. Esler, and W. S. Boyd. 2003. Plumage characteristics as an indicator of age class in the surf scoter. *Waterbirds* 26(1):56–61.

- Kuletz, K. J., C. S. Nations, B. Manly, A. Allyn, D. B. Irons, and A. Mcknight. 2011a. Distribution, abundance, and population trends of the Kittlitz's Murrelet "Brachyramphus brevirostris" in Prince William Sound, Alaska. *Marine Ornithology* 39:97–109.
- Kuletz, K. J., S. G. Speckman, J. F. Piatt, and E. A. Labunski. 2011b. Distribution, population status and trends of Kittlitz's Murrelet "Brachyramphus brevirostris" in Lower Cook Inlet and Kachemak Bay, Alaska. *Marine Ornithology* 39:85–95.
- Lance, B. K., D. B. Irons, S. J. Kendall, and L. L. McDonald. 2001. An evaluation of marine bird population trends following the *Exxon Valdez* oil spill, Prince William Sound, Alaska. *Marine Pollution Bulletin* 42(4):298–309.
- Litzow, M. A., and J. F. Piatt. 2003. Variance in prey abundance influences time budgets of breeding seabirds: evidence from pigeon guillemots *Cephus columba*. *Journal of Avian Biology* 34(1):54–64.
- Mcknight, A. E., K. M. Sullivan, D. B. Irons, S. W. Stephensen, and S. Howlin. 2008. Marine bird and sea otter population abundance of Prince William Sound, Alaska: trends following the T/V "Exxon Valdez" Oil Spill, 1989-2007. "Exxon Valdez" Oil Spill Restoration Project 050751. Anchorage, AK.
- Montevvecchi, W. A. 1993. Birds as indicators of change in marine prey stocks. Pages 217–266 in R. W. Furness and J. J. D. Greenwood, editors. *Birds as Monitors of Environmental Change* SE - 6. Springer Netherlands.
- Naves, L. C., and N. M. Braem. 2014. Alaska subsistence harvest of birds and eggs , 2012 , Alaska Migratory Bird Co-Management Council. Alaska Department of Fish and Game, Division of Subsistence. Technical Paper No. 397. Anchorage, Alaska.
- Piatt, J. F., and R. G. Ford. 1996. Proceedings of the Exxon Valdez Oil Spill Symposium: How many seabirds were killed by the "Exxon Valdez" oil spill? Pages 712–719. S. D. Rice, R. B. Spies, D. A. Wolf, and B. A. Wright, editors. American Fisheries Society Symposium 18, Bethesda, Maryland, USA.
- Piatt, J. F., and T. I. Van Pelt. 1997. Mass-mortality of guillemots (*Uria aalge*) in the Gulf of Alaska in 1993. *Marine Pollution Bulletin* 34(8):656–662.
- Piatt, J.F (ed.). 2002. Response of seabirds to fluctuations in forage fish density. Final Report to Exxon Valdez Oil Spill Trustee Council (Restoration Project 00163M) and Minerals Management Service (Alaska OCS Report 2002-068). Alaska Science Center, U.S. Geological Survey, Anchorage, Alaska.
- Piatt, J. F., W. Sydeman, and F. Wiese. 2007. Introduction: seabirds as indicators of marine ecosystems. *Marine Ecology Progress Series* 352:199–204.
- Speckman, S. G., J. F. Piatt, C. V. Minte-Vera, and J. K. Parrish. 2005. Parallel structure among environmental gradients and three trophic levels in a subarctic estuary. *Progress in Oceanography* 66(1):25–65.

- Suryan, R. M., D. B. Irons, M. Kaufman, J. Benson, P. G. R. Jodice, D. D. Roby, and E. D. Brown. 2002. Short-term fluctuations in forage fish availability and the effect on prey selection and brood-rearing in the black-legged kittiwake *Rissa tridactyla*. *Marine Ecology Progress Series* 236:273–287.
- Zador, S., H. G. L. Jr, T. TenBrink, and K. Aydin. 2013. Combined seabird indices show lagged relationships between environmental conditions and breeding activity. *Marine Ecology Progress Series* 485:245–258.

NEARSHORE MARINE BIRD SURVEYS: DATA SYNTHESIS, ANALYSIS AND RECOMMENDATIONS FOR SAMPLING FREQUENCY AND INTENSITY TO DETECT POPULATION TRENDS

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Introduction

The importance of marine birds to both pelagic and nearshore ecosystems has already been discussed in the marine bird introduction and will not be repeated here (Esler and Kuletz, this document). However, the role that marine birds play in both these the ecosystems clarifies how this project is linked to both the pelagic and benthic components of Gulf Watch Alaska (GWA). Nearshore marine bird monitoring currently has two ongoing efforts: 1) a synthesis and analysis of existing data to evaluate our ability to detect change (pelagic component) and 2) continuation of monitoring surveys (nearshore component; see chapter 4). Results from the first effort will help direct any future modifications of nearshore marine bird surveys.

Background: In the early 2000s, a holistic approach to nearshore marine ecosystem monitoring in the Gulf of Alaska (GOA) was developed (Dean and Bodkin 2006b). Concurrently, in 2001, a network of five national park units in southwest Alaska (SWAN) began the process of planning a long-term vital signs monitoring program (Bennett et al. 2006b). In partnership, these two programs successfully implemented long-term monitoring of the nearshore at several spatial and temporal scales as well as across trophic levels (Dean et al. 2014). Nearshore marine birds were identified as a vital sign for monitoring by SWAN and surveys began in 2006 at Katmai National Park and Preserve (KATM), and in 2007 at Kenai Fjords National Park (KEFJ). Currently, eight years of nearshore geo-referenced survey data exist from KATM and KEFJ, and four years from Prince William Sound (PWS). Data from PWS are being collected by US FWS. This work serves as a baseline for many aspects of the current GWA benthic monitoring program.

The original survey objective was to estimate long-term trends in the seasonal abundance of seabirds and sea ducks (Dean et al. 2014). This can be a difficult task when data prove to be highly variable. Bennett et al. (2006) suggested summarizing data annually but acknowledged that trends should be estimated after 10 years of initial data collection. In conjunction with Dean et al. 2014, the goal of the surveys was to be able to detect a significant decline (>50%) after 10 years of data collection. As we conducted annual summaries, several questions arose: 1) Is current survey intensity adequate to detect trends?; 2) How do we account for imperfect detection?; and 3) How do we correlate changes in abundance and distribution of marine birds to the other metrics also being measured by the nearshore component of GWA?

Early analyses of KATM and KEFJ marine bird survey results showed high between year variation in density estimates making trend detection difficult (Coletti et al. 2009). These early analyses resulted in CVs well over 0.50 (CV range of values from: 1.27 to 4.00) for all taxa, therefore confidence intervals for almost all species in all years encompassed zero, indicating little possibility to detect trends over time at our current sampling intensity. In an attempt to reduce CVs post data collection, subpopulation (domain) analysis was conducted based on shoreline habitat type (Coletti 2009).

Classification of transects into specific habitat types or domains reduced the variability of the density estimates and improved the power to detect change. However, a result of conducting subpopulation

(domain) analysis post survey is that the original sample size (number of transects) is reduced. In surveys similar to ours in Glacier Bay, AK, results showed that sample size was an important factor in determining CV's (Drew et al. 2008). Domain based designs generally have large samples sizes (Lehtonen and Pahkinen 2004) and by grouping each transect by habitat type prior to analysis, we essentially reduced sample size of the original survey, eliminating much of the efficiency gained by stratification. However, in our grouped analysis we did detect a decrease in variance, despite reduced sample sizes, that resulted in an improved power to detect change. From the 2009 analysis, we recommended exploring the possibility of re-allocating sampling efforts to specific habitat types, reducing variation that may enhance our ability to detect trends for most species of interest.

In the survey's current form, we anticipate that we will be able to detect large (>50%) changes in abundance for relatively common species, but have considered whether we can detect smaller levels of change as well as answer other questions of interest. Hence, to increase power, sources of variation should be identified and removed by method standardization or data analysis.

We recognize that variability is influenced by several factors including, but not limited to:

1. Individuals in groups were not independent.
2. Imperfect detection.
3. Habitat preferences by species. Habitat is treated as homogeneous across transects.
4. Annual variation in distribution (i.e., availability) relative to our sampling area – By availability we mean birds present and subject to counts.
5. Within-season variation in distribution – birds may utilize home ranges that are larger than individual transects, and any individual that utilizes a given transect during the season may or may not be present and subject to being detected and counted at any given sampling occasion. Birds may also utilize home ranges that overlap multiple transects.

Occupancy Approach

Existing data were characterized by widely spaced, very high counts due to temporary bird aggregations that were not tied to any specific site. We hypothesized that the large counts were adding to the problem of excess variance present in the count data. If animal locations were heterogeneous in time, we would not necessarily expect the same animals to occupy the same transects year after year. This would not bias counts, if birds were spatially randomly distributed. However, in the presence of aggregations, animals are no longer randomly distributed, which can lead to biased counts, and large interannual variation.

If the animals were not randomly distributed, perhaps we could assume that aggregations were randomly distributed at some spatial grain, permitting us to use bird occurrence as a surrogate for abundance in our monitoring program. Here, we explore using occupancy analysis to compute proportion of sites occupied as a state variable for the marine bird monitoring program. Occupancy, defined here as the probability of an area or unit being occupied, may provide useful information regarding species distribution, habitat preferences or availability by species, and rates of extinction and colonization by area (MacKenzie et al. 2006). As potential stressors to a system such as climate change, invasive species and other anthropogenic factors increase, understanding how a species or community is responding to those changes through changes in distribution may be informative for resource managers trying to assess park or regional resources and appropriate management actions.

Test case using harlequin duck data obtained from KATM in summer 2013

The harlequin duck (*Histrionicus histrionicus*) is a nearshore marine sea duck that primarily forages on benthic invertebrates (Goudie and Ankney 1986). Harlequin ducks were chosen for this analysis because they are fairly common (Coletti et al. 2014) and somewhat more evenly distributed along the KATM coast based on distribution maps created from past survey data.

Methods

We divided the shoreline of KATM and KEFJ into 5-km transects to obtain a population of sample units available for sampling. The transect lengths were adjusted to accommodate islands or groups of islands with less than 5 km of shoreline (minimum length = 2.5 km; recommendations from Drew et al 2008). Segments ≥ 2.5 km were large enough to contain entire bird aggregations (Bodkin 2011). Twenty-one transects were randomly selected for sampling (field method described below), such that a minimum of 20% of the park shoreline was surveyed. Five transects that occurred on small islands were > 5 km. These small transects were later grouped into 5km sample units, resulting in 19 5-km sample units. The surveys were not repeated during the year, and were not designed to account for imperfect detection and/or availability. To create spatial replicates for occupancy analysis, we divided sample units into 1 km segments in order to create spatial replicates used for occupancy analysis.

Surveys were conducted from small vessels (5-8 m length) navigating along selected coastline transects at speeds of 8-12 knots. All transects were run 100 m offshore and parallel to the shoreline. Two observers searched for marine birds at distances up to 100 m on either side of the vessel, including 100 m ahead of, behind, and over the vessel. One observer navigated the skiff, and surveyed the offshore portion of the transects. The second observer surveyed the shore side of the survey transects. All marine birds within the sampled area were identified and counted. A third team member entered the observations into a computer program (dLOG3) designed specifically for these surveys. Data collected included: species, count, sea state (Beaufort scale) and each observer's conditions (scale of 1-5, 1 being excellent and 5 being poor).

All harlequin duck observations from 2013 in KATM were joined (ArcGIS Spatial Join Tool) to the appropriate 1-km spatial sampling unit, thereby creating a five-unit spatial encounter history of bird observations (counts > 0) at each of the 19 sites. Each unit was assigned detection attributes such as: Beaufort, tide height at the time of the survey, actual length surveyed, and occupancy attributes such as: exposure level, and latitude.

Analysis

Presence-absence data present a dilemma for data analysis, because false absences can result in biased distribution and occurrence estimates. False absences can be broken into two components: detection (pertaining to the observer) and availability (pertaining to the animal). While it is possible to separate these factors, detection and availability are treated similarly by occupancy analysis. Typically, occupancy analysis is conducted on animal encounter histories generated through repeated surveys of sample units (sites) (MacKenzie et al. 2002, 2006). Observers visit sites a number of times, and record whether or not animals are detected or not during each visit. Sometimes spatial replicates are used in place of temporal replicates if sites are remote, and difficult to access (Hines et al. 2010, Reynolds and Renner 2014). The idea is that spatial variation is a surrogate for movement, and tells you something about the probability that animals will be in the unit during replicate surveys (Guillera-Arroita 2011).

We created encounter histories for 19 sample units (17 complete units, and 5 combined units), using harlequin duck data from 2013, and fit single season, 2-state occupancy models using the Unmarked package in R. Using four detection and three state covariates (Table 3-3), we evaluated eleven single-variable models (Table 3-4). We produced graphs illustrating how detection and occupancy varied with important predictors. We used empirical Bayesian analysis to obtain estimates of the Proportion of Sites Occupied (PSO) using all models with model weight >0.05. We then used model averaging (Burnham and Anderson 2002) to produce the final PSO estimate.

Table 3-3. Description of covariates used in models of harlequin duck occupancy in KATM.

Variable	Detection	Occupancy	Data type	Description
Length	X	X	Interval	Measure of survey effort, and a surrogate measure of coastline complexity.
Beaufort	X		Ordinal	Wind and sea conditions (1 – 3)
Tide height	X		Interval	Tide height relative to MHHW
Segment type	X		Categorical	Most common habitat type in the 1-k segment
Unit type		X	Categorical	Most common habitat type in the 5-k unit
Latitude		X	Interval	Geographic Y coordinate

Table 3-4. Model selection table for models single season of harlequin duck occupancy in KATM where p refers to the detection probability while psi is the probability of occupancy.

Model	nPars	AIC	delta	AICwt	cumltvWt
p(Length)psi(.)	3	108.70	0	0.32	0.32
p(Length)psi(Length)	4	109.04	0.34	0.27	0.60
p(Length)psi(Type)	6	109.81	1.11	0.19	0.79
p(Length)psi(Latitude)	4	110.70	2.00	0.12	0.91
p(.),psi(Length)	3	111.63	2.93	0.08	0.98
p(.),psi(.)	2	116.51	7.81	0.01	0.99
p(.),psi(Type)	5	117.08	8.38	0.01	1
p(tide)psi(.)	3	117.75	9.04	0.00	1
p(.),psi(Latitude)	3	118.51	9.80	0.00	1
p(type)psi(.)	5	119.83	11.13	0.00	1
p(Beaufort)psi(.)	4	120.32	11.62	0.00	1

Results and Discussion

Transect length was the most important predictor of both detection and occupancy, occurring in all of the models with AIC < the no-covariate model (Table 3-3). Both detection and occupancy increased with increasing transect length (Table 3-4). There was weak evidence of heterogeneity in occupancy with sites with different habitat types (Table 3-3). Although there was much variation, protected, and semi-protected sites had a slightly lower probability of being occupied than exposed sites (Figure 3-16). A slight latitudinal gradient was observed, where the probability of occupancy increased with increasing latitude (Table 3-3). The model-averaged proportion of sites occupied was 0.87 (90% CI = 0.77 - 0.97).

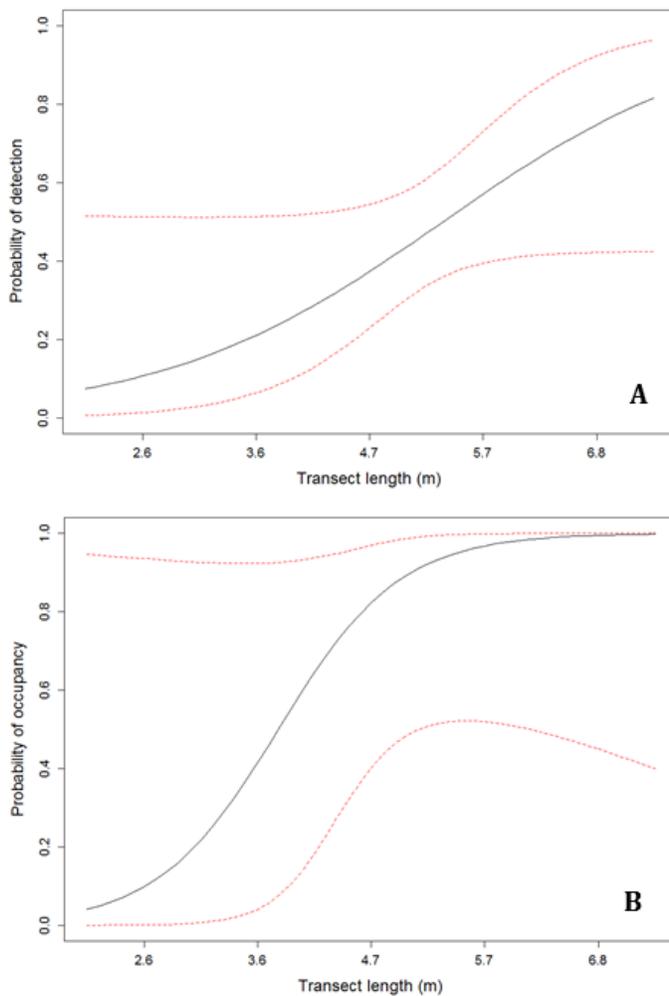


Figure 3-15. Relationship of harlequin duck (A) detection and (B) occupancy with transect length in KATM. The black line represents the likelihood estimate, and the red-dashed lines represent the 95% confidence intervals.

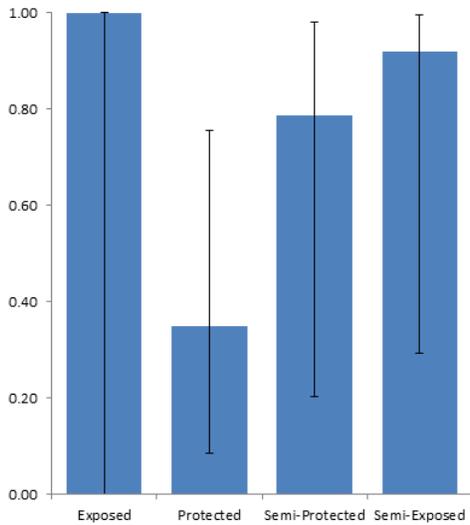


Figure 3-16. Probability of site occupancy for four habitat types in KATM.

Because a unit of occupancy is spatially defined, we also assume we will be able to quantify metrics such as prey availability, habitat type, exposure, shoreline complexity, water quality parameters, etc. to that same spatial unit(s). Changes or shifts in site occupancy could theoretically be correlated to other physical or biological drivers of the system. This becomes particularly important in the face of climate change as potential stressors to a system increase. Understanding how a species or community is responding to those stressors through changes in distribution will be informative for resource managers to implement appropriate management actions.

Conclusions and Recommendations

From this preliminary analysis, how survey effort is allocated is critical. In the initial design, transects were five km long. However, during standard skiff surveys, depending on tide height, conditions and the abilities of the skiff driver, those transects could be significantly more or less than five km in length. This equates to variable effort per transect. While standardizing length would be ideal, we also recognize that it is not feasible. We suggest effort is modeled rigorously. This could include time on transect or actual length travelled during a single transect survey. There was also high model-selection uncertainty (all models have nearly the same AIC). This indicates that there is still some un-modeled heterogeneity and this may be improved by calculating more appropriate habitat covariates. For example, assigning habitat classes that take into account both shoreline type and bathymetry.

Sample size was also an issue in the preliminary analysis. Even though we had five replicate encounter histories, there were large uncertainties associated with estimates (Figure 3-15 A and B confidence intervals). Essentially, the limited number of transects does not capture the level of heterogeneity in the existing data. Despite this, the current sampling protocol represented the maximum effort that can be expended on surveys given logistical constraints. While we are not in a position to recommend adding more transects at this point, further discussion and analysis may have us: 1) reducing the scope of the

monitoring program by focusing our efforts in specific habitats; 2) increasing the number of transects sampled; 3) changing the spatial grain of sampling (sample unit size); and 4) considering more complex model structures in a fully Bayesian framework. The optimal course of action will depend on refinement of monitoring objectives. For example, the estimated proportion of sites occupied was close to one, and near the upper boundary of that considered to be “meaningful” for occupancy analysis (MacKenzie et al. 2006). Reducing the sample unit size could remedy this problem for harlequin ducks, but may reduce the effectiveness of the sampling design for a species that isn’t as common. Any discussion of objectives should address the following: spatial extent of analysis, spatial grain of analysis, target species, hypothesized population drivers, and feasible courses of action (e.g. management or conservation) if change is detected.

References

- Bennett, A. J., W. L. Thompson, and D. C. Mortenson. 2006. Vital signs monitoring plan, Southwest Alaska Network Inventory and Monitoring Program. Anchorage, AK.
- Bodkin, J. L. 2011. SOP for Conducting Marine Bird and Mammal Surveys - Version 4.1. Southwest Alaska Inventory and Monitoring Network. Natural Resource Report NPS/SWAN/NRR-2011/392. Fort Collins, Colorado.
- Burnham, K. P., and D. R. Anderson. 2002. Model Selection and Mult-model Inference: a practical information-theoretic approach Second Edi. Springer, New York, New York, USA.
- Coletti, H. A., J. L. Bodkin, T. A. Dean, and K. A. Kloecker. 2009. Nearshore Marine Vital Signs Monitoring in the Southwest Alaska Network of National Parks. Natural Resource Technical Report NPS/SWAN/NRTR - 2009/252. Fort Collins, Colorado.
- Coletti, H. A., T. A. Dean, K. A. Kloecker, and B. E. Ballachey. 2014. Nearshore Marine Vital Signs Monitoring in the Southwest Alaska Network of National Parks: 2012. Natural Resource Technical Report NPS/SWAN/NRTR - 2014/843. Fort Coliins, Colorado.
- Dean, T. A., and J. L. Bodkin. 2006. Sampling Protocol for the Nearshore Restoration and Ecosystem Monitoring (N-REM) Program (Nearshore Restoration and Ecosystem Monitoring Research Project G-050750), US Geological Survey, Alaska Science Center. Anchorage, AK.
- Dean, T. A., J. L. Bodkin, and H. A. Coletti. 2014. Protocol Narrative for Nearshore Marine Ecosystem Monitoring in the Gulf of Alaska: Version 1.1. Natural Resource Report NPS/SWAN/NRR - 2014/756. Fort Coliins, Colorado.
- Drew, G. S., S. G. Speckman, J. F. Piatt, J. M. Burgos, and J. L. Bodkin. 2008. Survey Design Considerations for Monitoring Marine Predator Populations in Glacier Bay, Alaska: Results and Post-hoc Analyses of Surveys Conducted in 1999-2003. USGS Final Report.
- Goudie, R. I., and C. D. Ankney. 1986. Body Size, Activity Budgets, and Diets of Sea Ducks Wintering in Newfoundland. *Ecology* 37:1475–1482.

- Guillera-Aroita, G. 2011. Impact of sampling with replacement in occupancy studies with spatial replication. *Methods in Ecology and Evolution* 2(4):401–406.
- Hines, J. E., J. D. Nichols, J. A. Royle, D. I. MacKenzie, A. M. Gopalaswamy, N. S. Kumar, and K. U. Karanth. 2010. Tigers on trails: occupancy modeling for cluster sampling. *Ecological Applications* 20(5):1456–1466.
- Lehtonen, R., and E. Pahkinen. 2004. *Practical Methods for Design and Analysis of Complex Surveys*. Page 349. Second Edi. John Wiley and Sons.
- MacKenzie, D. I., J. D. Nichols, G. B. Lachman, S. Droege, J. A. Royle, and C. A. Langtimm. 2002. Estimating site occupancy rates when detection probabilities are less than one. *Ecology* 83(8):2248–2255.
- MacKenzie, D. I., J. D. Nichols, J. A. Royle, and C. A. Langtimm. 2006. *Occupancy Estimation and Modeling: Inferring Patterns and Dynamics of Species Occurrence*. Page 324. Academic Press.
- Reynolds, J. H., and H. M. Renner. 2014. Using patch occupancy models to estimate area of crevice-nesting seabird colonies. *The Condor* 116(3):316–324.

RESEARCH SUMMARY: TEMPORAL CHANGE IN A SUBARCTIC MARINE BIRD COMMUNITY LINKED TO HABITAT AND CLIMATE CHANGE

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Introduction

The U.S. Fish and Wildlife Service conducted boat-based surveys of marine birds in Prince William Sound (PWS), Alaska, over a 23-year period following the 1989 *Exxon Valdez* oil spill (EVOS). The goal of this long-term study was to identify changes in marine bird populations, particularly in oiled and unoiled portions of PWS (Irons et al. 2000, Lance et al. 2001). In addition to the oil spill, the marine ecosystems of PWS have been affected by climate variability (Spies 2007). Here, we use this long-term survey data set to investigate the factors that affected patterns of abundance and community composition, across space and time, within the marine bird community of PWS.

The highly productive marine ecosystems of the Northern Gulf of Alaska (GOA) have been affected by several perturbations over the past 25 years (Spies 2007). These ecological perturbations have included a major anthropogenic disturbance, the 1989 EVOS. Oil from the *Exxon Valdez* polluted 1750 km of shoreline (Wolfe et al. 1994), and resulted in extensive acute mortality of marine organisms, including an estimated 250,000 marine birds (Piatt and Ford 1996). In some shoreline locations, *Exxon Valdez* hydrocarbons remained in sediments for many years after the spill (Short et al. 2004a). In those locations, chronic oil exposure had prolonged, harmful effects on some marine bird species that are associated with shoreline sediments (Iverson and Esler 2010).

The EVOS occurred within a dynamic marine ecosystem (Spies 2007). Atmospheric forcing of the northeastern Pacific Ocean causes low-frequency variability in ocean circulation, temperature, salinity, and nutrients (Chhak et al. 2009, Di Lorenzo et al. 2009). These processes affect the quantity, distribution, and timing of primary production, the transport of larval organisms, and the growth and survival of zooplankton and fish (Eslinger et al. 2001, Hunt and McKinnell 2006). Concurrent with climatic fluctuations, tremendous changes have occurred in the marine food webs of the GOA (Francis et al. 1998, Hare and Mantua 2000). These included changes in the abundance of some mid-trophic species that are important prey for many seabirds (Anderson and Piatt 1999).

Marine birds are a conspicuous and ecologically diverse species group, and as such, can be valuable indicators of changes in marine ecosystems. Marine birds use habitats from the intertidal to the pelagic, and a wide range of food resources (Lack 1967, Schreiber and Burger 2001). The responses of marine bird species to environmental perturbations may be expected to be shaped by traits such as habitat use and diet. For this reason, patterns of change within marine bird communities can be indicative of causal

factors. For example, declines of many piscivorous marine bird populations in PWS paralleled a climatic shift in the late 1970's which affected prey availability (Agler et al. 1999).

In order to better understand the dynamics of a marine bird community that has experienced the simultaneous effects of a major oil spill and climate variability, we evaluated data collected during a long-term marine bird survey program in PWS. Focusing on an ecologically diverse group of marine bird taxa, we evaluated relationships between spatial patterns of abundance and seabird community composition (i.e., community structure) and habitat. We then evaluated changes in abundance and community composition over time, and whether such changes were correlated with climate. Finally, we determined whether genera that co-occurred in the same locations also tended to have similar changes in abundance over time. If so, it would suggest that the factors causing ecological changes were associated with the factors that shaped spatial patterns of community structure.

Methods

Our study area was the inside waters of PWS (Figure 3-17), an area of approximately 9000 km². Marine bird surveys were conducted during July during 12 years within the interval 1989-2012. Surveys were conducted from 7.6-m boats, using 200m-wide strip-transects. The study employed a stratified-randomized sampling design, with shoreline, coastal, and pelagic strata (Agler et al. 1999, Lance et al. 2001, Golet et al. 2002). The same transects, totaling approximately 2000 linear km, were surveyed each year. We included 18 genera of marine birds in our analyses (Table 3-5).

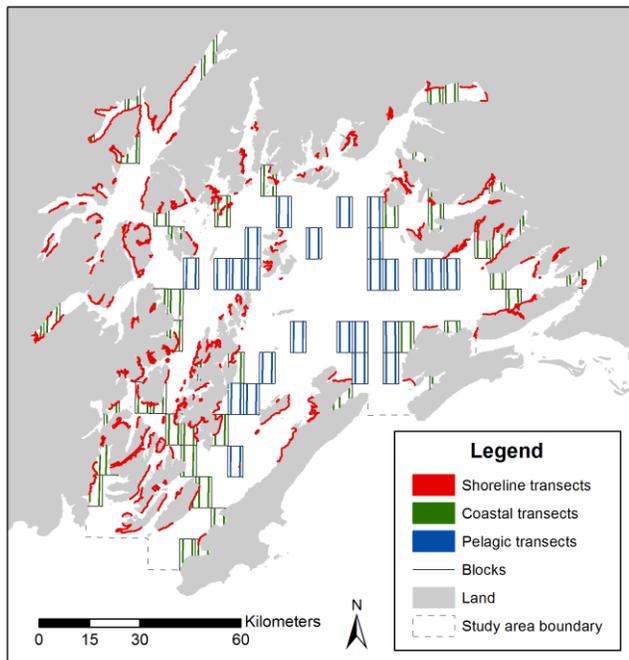


Figure 3-17. Location of marine bird survey transects within Prince William Sound, Alaska.

Table 3-5. Mid-summer abundance trends for 18 evaluated genera of marine birds from Prince William Sound, Alaska over the period 1989-2012.

Common name	Habitat group	Prey group	Abundance trend
Loons	Coastal	Piscivore	No change
Storm-petrels	Offshore	Planktivore	Declined
Cormorants	Coastal	Piscivore	Increased
Great blue heron	Shoreline	Piscivore (& intertidal)	Increased
Harlequin duck	Shoreline	Benthic	Increased
Scoters	Coastal	Benthic	No change
Goldeneyes and bufflehead	Shoreline	Benthic	No change
Mergansers	Shoreline	Piscivore	No change
Black oystercatcher	Shoreline	Intertidal	No change
<i>Larid</i> gulls	Coastal	Piscivore & intertidal	No change
Bonaparte's gull	Coastal	Piscivore & planktivore	Declined
Black-legged kittiwake	Coastal	Piscivore & planktivore	No change
Terns	Coastal	Piscivore	Declined
Jaegers	Offshore	Piscivore	Declined
Murres	Offshore	Piscivore	No change
Pigeon guillemot	Coastal	Piscivore (& benthic)	Declined
Murrelets	Coastal	Piscivore & planktivore	Declined
Puffins	Offshore	Piscivore	Declined

We evaluated spatial patterns of community structure using statistical methods that characterize patterns within multivariate data (Nonmetric Multidimensional Scaling) (Kruskal 1964). This analysis was based on abundance values for each genus, averaged over all survey years, within each transect. We then evaluated relationships between community structure and habitat variables (Generalized Additive Models) (Wood 2011). We obtained data on shoreline substrate composition and exposure to wave energy from the ShoreZone Coastal Habitat Mapping Program (Harney et al. 2008). We calculated water depth from a digital elevation model (Caldwell et al. 2011), and distance from shore from a digital shoreline map (ADNR 1998). We measured sea surface temperature and sea surface salinity during surveys. We

evaluated habitat associations of genera using weighted averaging, based on abundance values within transects (McCune et al. 2002). We also classified the primary prey types utilized by genera based on the literature, with four categories: planktivore (e.g., euphausiids and copepods), piscivore (fishes), benthic (e.g., bivalves, gastropods, worms, and small crabs), and intertidal (shoreline organisms).

To evaluate changes in abundance and community composition over time, we first estimated annual abundance values for PWS as a whole and for each evaluated genus (Bootstrap Resampling) (Manly 2006). For each genus, we then estimated the rate of change in abundance, or population trend, over the 23-year study period (Weighted Nonlinear Regression) (Bates and Watts 1988). We also evaluated changes in community composition among years (Nonmetric Multidimensional Scaling), using annual abundance estimates. We then evaluated the correlation between temporal patterns of community composition and two modes of climatic variability, the Pacific Decadal Oscillation (Zhang et al. 1997, Mantua et al. 1997a) and the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008), across annual to decadal time-scales of biological response to climate forcing (damped autoregressive forcing-response relationship) (Di Lorenzo and Ohman 2013). To determine whether patterns of temporal change were similar among co-occurring genera of marine birds, we evaluated relationships between spatial patterns of community structure and temporal changes in abundance and community composition (Weighted Multiple Linear Regression).

Results and Discussion

Spatial patterns of community composition

We found the strongest spatial pattern of marine bird community composition in PWS occurred along a gradient that was strongly related to distance to shore and water depth. The marine food webs of the GOA are also structured along an environmental gradient from the littoral to the oceanic (Parsons 1986). Sources of primary productivity differ along this gradient. In intertidal and shallow nearshore waters, the majority of primary production is generated by sea grasses, macrophytes, and benthic microalgae, with relatively little generated by phytoplankton in most habitats (Mann 2009). In contrast, in pelagic waters, most primary production is generated by phytoplankton (Parsons 1986). Thus, the dominant compositional gradient we observed within the marine bird community of PWS parallels important aspects of food web structure.

We found that a secondary spatial gradient in marine bird community composition was strongly related to variation in sea surface salinity, and moderately related to variation in shoreline exposure to wave energy. In PWS, sea surface salinity values are generally lowest where freshwater enters the ocean at the inner parts of bays and fjords. Salinity and exposure are moderately correlated along what we describe as an “estuarine-marine” environmental gradient. Several other studies within fjord and estuarine systems in the northern GOA have found that mid- or upper-trophic level communities were organized along environmental gradients that were related, in part, to salinity (Speckman et al. 2005, Arimitsu et al. 2012, Renner et al. 2012). These results are indicative of the importance of freshwater inputs to GOA coastal ecosystems.

Temporal patterns of abundance and community composition

We found that, over the 23-year study period, tremendous changes had occurred, both in the abundance of individual marine bird genera, and in the composition of the marine bird community as a whole. We found that seven of 18 evaluated genera of marine birds declined in abundance over the study period,

while three increased in abundance (Table 1). These changes were large in magnitude; six genera experienced cumulative declines in excess of two-thirds of their numbers.

We also evaluated variability in community composition among years, and found that the majority of variability among years was explained by changes in the abundance of particular genera over long time periods. This pattern was correlated with indices of climate variability at time-scales consistent with demographic responses of marine birds to climate forcing. We also found that a secondary mode of temporal variability in community composition among years was characterized by short-term fluctuations. These fluctuations were correlated with climate variability at an annual time-scale. They also corresponded to indicators of foraging conditions elsewhere in the GOA, including a common murre (*Uria aalge*) mass-mortality event (Piatt and Van Pelt 1997) and a time-series of nestling diets for black-legged kittiwake (*Rissa tridactyla*) at Middleton Island (Hatch 2013a). These observations are indicative of inter-annual movements of marine birds between PWS and the GOA, likely due to climate fluctuations that affected foraging conditions.

Relationships between spatial and temporal patterns

We evaluated rates of change in the abundance of genera of marine birds over time in relation to the responses of genera to environmental gradients that structured the community as a whole. We found that rates of change were more similar among genera that generally co-occurred in the same habitats than would be expected by chance. Rates of increase in abundance were likely to be greater than average for genera associated with relatively shallow shoreline habitat, and rates of decline were likely to be greater than average for genera associated with deep offshore habitat. Furthermore, all genera that declined primarily feed on fish or zooplankton. Our results are congruent with those of Agler et al. (1999), who concluded that, in PWS, piscivorous taxa of marine birds were more likely than non-piscivorous taxa to have declined in abundance between 1972 and the early 1990s. This suggests that the community-level pattern of change we observed likely began prior to 1989. Our findings are indicative of changes in pelagic components of PWS food webs.

Conservation implications

The EVOS affected many of the marine bird taxa we evaluated in this study (EVOSTC 2010).

Immediately following the oil spill, diving species of marine birds experienced extensive acute mortality, while surface-feeding species were better able to avoid contact with oil (Piatt et al. 1990). In nearshore areas where oil persisted in sediments, chronic hydrocarbon exposure affected some species that forage in benthic and intertidal habitats (Trust et al. 2000, Golet et al. 2002, Esler et al. 2010a). Nevertheless, we found that during summer, throughout PWS as a whole and over a 23-year period following the EVOS, few shoreline-associated genera of marine birds experienced sustained declines in abundance. In contrast, we found that many coastal and offshore-associated genera of marine birds declined, including both diving and surface-feeding piscivorous and planktivorous taxa. Concurrent declines occurred in both piscivorous marine mammals (Frost et al. 1999, Trites et al. 2007) and planktivorous schooling forage fishes (Hulson et al. 2008). The most parsimonious general explanation for these synchronous changes is alteration of the pelagic food webs of PWS. Coincident with these ecological changes, broad-scale changes occurred in the climate systems of the northeastern Pacific Ocean, suggesting that a bottom-up explanation for observed ecological changes is plausible. Our findings indicate that changes in pelagic food webs have likely contributed to the lack of recovery of some piscivorous marine bird taxa from the direct effects of the EVOS.

Acknowledgments

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References

- ADNR. 1998. Alaska Coastline 1:63:360. Alaska Department of Natural Resources, Information Resource Management. Anchorage, Alaska.
- Agler, B. A., S. J. Kendall, D. B. Irons, and S. P. Klosiewski. 1999. Declines in Marine Bird Populations in Prince William Sound, Alaska Coincident with a Climatic Regime Shift. *Waterbirds: The International Journal of Waterbird Biology* 22(1):98–103.
- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Marine Ecology Progress Series* 189:117–123.
- Arimitsu, M. L., J. F. Piatt, E. N. Madison, J. S. Conaway, and N. Hillgruber. 2012. Oceanographic gradients and seabird prey community dynamics in glacial fjords. *Fisheries Oceanography* 21(2-3):148–169.
- Bates, D. M., and D. G. Watts. 1988. *Nonlinear Regression Analysis and Its Applications* Second Edi. John Wiley & Sons, Inc., Hoboken, NJ, USA.
- Caldwell, R. J., B. W. Eakins, and E. Lim. 2011. Digital elevation models of Prince William Sound, Alaska: Procedures, data sources, and analysis. Technical Report, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center. Boulder, Colorado.
- Chhak, K. C., E. Di Lorenzo, N. Schneider, and P. F. Cummins. 2009. Forcing of Low-Frequency Ocean Variability in the Northeast Pacific*. *Journal of Climate* 22(5):1255–1276.
- Esler, D., K. A. Trust, B. E. Ballachey, S. A. Iverson, T. L. Lewis, D. J. Rizzolo, D. M. Mulcahy, A. K. Miles, B. R. Woodin, J. J. Stegeman, J. D. Henderson, and B. W. Wilson. 2010. Cytochrome P4501A biomarker indication of oil exposure in harlequin ducks up to 20 years after the Exxon Valdez oil spill. *Environmental toxicology and chemistry / SETAC* 29(5):1138–45.
- Eslinger, D. L., R. T. Cooney, C. P. Mcroy, A. Ward, T. C. Kline, E. P. Simpson, J. Wang, and J. R. Allen. 2001. Plankton dynamics: observed and modelled responses to physical conditions in Prince William Sound, Alaska. *Fisheries Oceanography* 10:81–96.
- EVOSTC. 2010. “Exxon Valdez” Oil Spill Restoration Plan: 2010 update on injured resources and services. “Exxon Valdez” Oil Spill Trustee Council, Anchorage, Alaska. Anchorage, Alaska.

- Francis, R. C., S. R. Hare, A. B. Hollowed, and W. S. Wooster. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. *Fisheries Oceanography* 7(1):1–21.
- Frost, K. J., L. F. Lowry, and J. M. Hoef. 1999. Monitoring the trend of harbor seals in Prince William Sound, Alaska, after the Exxon Valdez oil spill. *Marine Mammal Science* 15(2):494–506.
- Golet, G. H., P. E. Seiser, A. D. McGuire, D. D. Roby, J. B. Fischer, K. J. Kuletz, D. B. Irons, T. A. Dean, and S. C. Jewett. 2002. Long-term direct and indirect effects of the “Exxon Valdez” oil spill on pigeon guillemots in Prince William Sound, Alaska. *Marine Ecology Progress Series* 241:287–304.
- Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47(2-4):103–145.
- Harney, J. N., M. C. Morris, and J. R. Harper. 2008. ShoreZone coastal habitat mapping protocol for the Gulf of Alaska. Report prepared for The Nature Conservancy, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, and the Alaska State Department.
- Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. *Marine Ecology Progress Series* 477:271–284.
- Hulson, P.-J. F., S. E. Miller, T. J. Quinn, G. D. Marty, S. D. Moffitt, and F. Funk. 2008. Data conflicts in fishery models: incorporating hydroacoustic data into the Prince William Sound Pacific herring assessment model. *ICES Journal of Marine Science* 65(1):25–43.
- Hunt, G. L., and S. McKinnell. 2006. Interplay between top-down, bottom-up, and wasp-waist control in marine ecosystems. *Progress in Oceanography* 68(2-4):115–124.
- Irons, D. B., S. J. Kendall, W. P. Erickson, L. L. McDonald, and B. K. Lance. 2000. Nine Years after the “Exxon Valdez” Oil Spill: Effects on marine bird populations in Prince William Sound, Alaska. *The Condor* 102(4):723.
- Iverson, S. A., and D. Esler. 2010. Harlequin Duck population injury and recovery dynamics following the 1989 “Exxon Valdez” oil spill. *Ecological Applications* 20(7):1993–2006.
- Kruskal, J. B. 1964. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* 29(1):1–27.
- Lack, D. 1967. Interrelationships in breeding adaptations as shown by marine birds, 24-30 July, 1966. *Proceedings of the XIV International Ornithological Congress*. Oxford, UK.
- Lance, B. K., D. B. Irons, S. J. Kendall, and L. L. McDonald. 2001. An Evaluation of Marine Bird Population Trends Following the Exxon Valdez Oil Spill, Prince William Sound, Alaska. *Marine Pollution Bulletin* 42(4):298–309.

- Di Lorenzo, E., J. Fiechter, N. Schneider, A. Bracco, A. J. Miller, P. J. S. Franks, S. J. Bograd, A. M. Moore, A. C. Thomas, W. Crawford, A. Peña, and A. J. Hermann. 2009. Nutrient and salinity decadal variations in the central and eastern North Pacific. *Geophysical Research Letters* 36(14):L14601.
- Di Lorenzo, E., and M. D. Ohman. 2013. A double-integration hypothesis to explain ocean ecosystem response to climate forcing. *Proceedings of the National Academy of Sciences of the United States of America* 110(7):2496–9.
- Di Lorenzo, E., N. Schneider, K. M. Cobb, P. J. S. Franks, K. Chhak, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchitser, T. M. Powell, and P. Rivière. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* 35(8):L08607.
- Manly, B. F. J. 2006. *Randomization, Bootstrap and Monte Carlo Methods in Biology*, Third Edition. Page 480. CRC Press.
- Mann, K. H. 2009. *Ecology of Coastal Waters: With Implications For Management*. Page 432. John Wiley & Sons.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society* 78(6):1069–1079.
- McCune, B., J. B. Grace, and D. L. Urban. 2002. *Analysis of Ecological Communities*. Page 300. MjM Software Design.
- Parsons, T. R. 1986. Ecological relations. In: *The Gulf of Alaska: Physical environment and biological resources*. U.S. Department of Commerce, National Oceanographic and Atmospheric Administration. Pages 561–570. D. W. Hood and S. T. Zimmerman, editors. U.S. Government Printing Office, Washington D.C.
- Piatt, J. F., and R. G. Ford. 1996. Proceedings of the Exxon Valdez Oil Spill Symposium: How many seabirds were killed by the “Exxon Valdez” oil spill? Pages 712–719. S. D. Rice, R. B. Spies, D. A. Wolf, and B. A. Wright, editors. American Fisheries Society Symposium 18, Bethesda, Maryland, USA.
- Piatt, J. F., and T. I. Van Pelt. 1997. Mass-mortality of guillemots (*Uria aalge*) in the Gulf of Alaska in 1993. *Marine Pollution Bulletin* 34(8):656–662.
- Renner, M., M. L. Arimitsu, J. F. Piatt, and M.-J. Rochet. 2012. Structure of marine predator and prey communities along environmental gradients in a glaciated fjord. *Canadian Journal of Fisheries and Aquatic Sciences* 69(12):2029–2045.
- Schreiber, E. A., and J. Burger. 2001. Seabirds in the marine environment. In *Biology of marine birds*. Pages 1–15. E. A. Schreiber and J. Burger, editors. CRC Press, Boca Ranton, Florida.

- Short, J. W., M. R. Lindeberg, P. M. Harris, J. M. Maselko, J. J. Pella, and S. D. Rice. 2004. Estimate of oil persisting on the beaches of Prince William Sound 12 years after the Exxon Valdez oil spill. *Environmental science & technology* 38(1):19–25.
- Speckman, S. G., J. F. Piatt, C. V. Minte-Vera, and J. K. Parrish. 2005. Parallel structure among environmental gradients and three trophic levels in a subarctic estuary. *Progress in Oceanography* 66(1):25–65.
- Spies, R. B. 2007. Agents of Ecosystem Change. Pages 171–257 R. B. Spies, editor Long-term Ecological Change in the Northern Gulf of Alaska. Elsevier.
- Trites, A. W., A. J. Miller, H. D. G. Maschner, M. A. Alexander, S. J. Bograd, J. A. Calder, A. Capotondi, K. O. Coyle, E. Di Lorenzo, B. P. Finney, E. J. Gregr, C. E. Grosch, S. R. Hare, G. L. Hunt, J. Jahncke, N. B. Kachel, H.-J. Kim, C. Ladd, N. J. Mantua, C. Marzban, W. Maslowski, R. Mendelssohn, D. J. Neilson, S. R. Okkonen, J. E. Overland, K. L. Reedy-Maschner, T. C. Royer, F. B. Schwing, J. X. L. Wand, and A. J. Winship. 2007. Bottom-up forcing and the decline of Steller sea lions (*Eumetopias jubatus*) in Alaska: assessing the ocean climate hypothesis. *Fisheries Oceanography* 16(1):46–67.
- Trust, K. A., D. Esler, B. R. Woodin, and J. J. Stegeman. 2000. Cytochrome P450 1A Induction in Sea Ducks Inhabiting Nearshore Areas of Prince William Sound, Alaska. *Marine Pollution Bulletin* 40(5):397–403.
- Wolfe, D. A., M. J. Hameedi, J. A. Galt, G. Watabayashi, J. Short, C. O’Claire, S. Rice, J. Michel, J. R. Payne, J. Braddock, S. Hanna, and D. Sale. 1994. The fate of the oil spilled from the “Exxon Valdez”. *Environmental science & technology* 28(13):560A–8A.
- Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 73(1):3–36.
- Zhang, Y., J. M. Wallace, and D. S. Battisti. 1997. ENSO-like Interdecadal Variability: 1900–93. *Journal of Climate* 10(5):1004–1020.

RESEARCH SUMMARY: LONG-TERM MONITORING OF SEABIRD ABUNDANCE AND HABITAT ASSOCIATIONS DURING LATE FALL AND WINTER IN PRINCE WILLIAM SOUND

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Bishop, M.A., J.T. Watson, K. Kuletz and T. Morgan. 2015. Pacific herring consumption by marine birds during winter in Prince William Sound, Alaska. *Fisheries Oceanography* 24(1) 1-13.

Dawson, N.M., M.A. Bishop, K.J. Kuletz, and A. F. Zuur. *In press*. Using ships of opportunity to assess winter habitat associations of seabirds in subarctic coastal Alaska. *Northwest Science*. Accepted October 2014.

Bishop, M.A., and K.J. Kuletz. Winter marine bird assemblages in bays of southcentral Alaska. (*manuscript in prep*).

Introduction

Vessel-based research in marine waters is expensive and as a result it is often difficult to sustain funding for long-term monitoring projects. In the case of marine bird monitoring, one cost-effective alternative to a dedicated vessel is to place marine bird observers onboard “ships of opportunity”. While in some cases these are commercial vessels (*c.f.* Batten et al. 2006), more often observers have been placed on research vessels already conducting oceanography or fisheries surveys, thereby providing a situation where data can be integrated across projects. In addition, ships of opportunity can provide an increase in spatial and temporal coverage that otherwise may not be affordable. In Alaska, ships of opportunity are currently being used by the US Fish and Wildlife Service (USFWS) to conduct surveys of marine birds in the Bering Sea (Kuletz et al. 2008), Chukchi Sea, Beaufort Sea, Arctic Ocean and the Gulf of Alaska (K. Kuletz, USFWS, pers. comm.).

Beginning in 2007, the PWS Science Center (P.I. Bishop) and the USFWS (P.I. Kuletz) collaborated in an EVOS-sponsored project to place observers onboard research vessels during winter. In 2012, this research project became part of the GulfWatch Program and under the direction of PI Bishop. The project has expanded from using EVOS-sponsored PWS Science Center juvenile herring surveys and NOAA Humpback Whale surveys as platforms to include two additional ships of opportunity, (Alaska Department of Fish and Game and Ocean Tracking Network Maintenance Cruise). Currently marine bird observers are placed onboard ships during four cruises each winter: October, November, December, and February.

Objectives of this study include:

- 1) Characterize the spatial and temporal abundance of seabirds in PWS during late fall and winter.
- 2) Model species abundance in relation to biological and physical environmental variables.
- 3) Assess seabird habitat associations within and between winters.
- 4) Relate species composition and distribution to prey fields.
- 5) Identify critical marine habitats used by seabirds during late fall and winter.

Here we summarize key findings from our research conducted since 2007. Included in this summary are two manuscripts that are currently *in press*, and one manuscript in preparation, as well as preliminary analyses of the past seven years data that is in progress.

Study area and Methods

Marine bird surveys cover the bays, passages and open waters of Prince William Sound. Over the past seven winters, 27 surveys have been conducted (Figure 3-18). Seabird observations were conducted using established U.S. Fish and Wildlife Service protocols adapted for GPS-integrated data entry programs (USFWS 2007). One experienced observer using 10x binoculars recorded number of birds occurring within a strip transect width of 300 m (150 m both sides and ahead of the boat). The observer recorded observations directly into a laptop computer using the program Dlog (R.G. Ford Consulting, Portland OR).

Depending on the analyses, we calculated density (birds/ km²) of each seabird species or species group for each 1 kilometer of survey trackline or for each 3 km of survey trackline. For habitat modeling, we spatially matched explanatory variables to the midpoint of each transect. We then modeled habitat associations for select species using a two-stage hurdle model (Zuur et al. 2012; Dawson et al. *in press*). More recently we have incorporated detection variables into our models and are using zero-inflated Poisson (ZIP) models (Stocking et al. *in progress*). To determine species composition in bays we used multivariate analyses (Figure 3-16). Using Primer 6 (Clarke and Warwick 2001), analysis of similarity test was used to test the significance of observed differences between survey months (November and March) and study bays. To determine which bird species contributed to differences between site assemblages, we calculated one-way similarity of percentages.

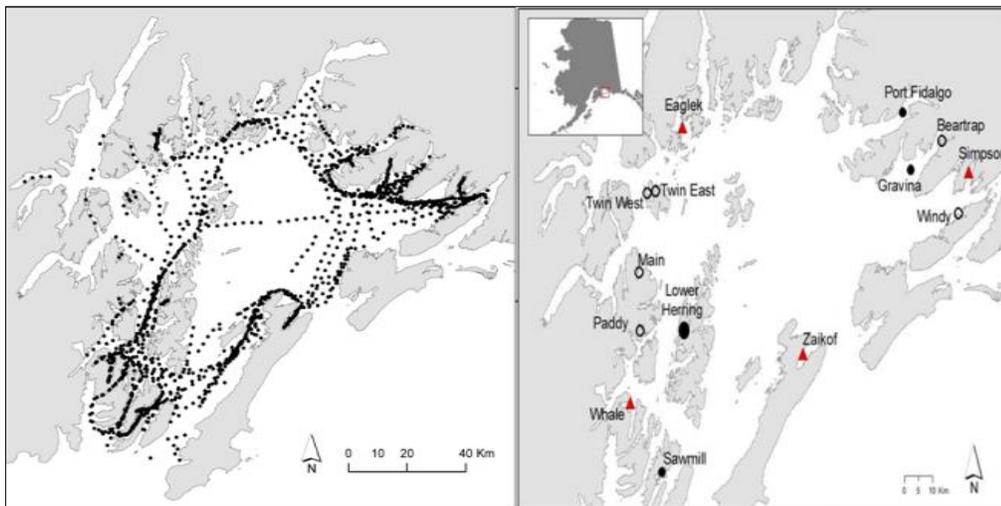


Figure 3-18 Left: Midpoints of 3-km segments surveyed for marine birds in Prince William Sound over seven winters, 2007-2014. Right: Bays surveyed in conjunction with hydroacoustic herring surveys, November and March during winters 2007/08 through 2011/2012. Red triangles = four core bays sampled five winters; solid circles = bays sampled 2-3 winters; open circles = bays sampled one winter. Since November 2012, hydroacoustic herring and marine bird surveys are conducted in bays (n = 9) during November only.

Key Findings

Herring Consumption in Winter by Marine Birds (from Bishop et al. 2015)

Our bioenergetics model results highlight the importance of herring to marine birds in PWS during winter and suggest that predation by marine birds may have an important top-down effect on the PWS herring population. The estimated total herring consumption by marine birds averaged 2409 ± 950 t per year for the 10 winters with birds consuming more juvenile ($\bar{x} = 1596 \pm 820$ t) than adult ($\bar{x} = 812 \pm 479$ t) herring in all winters (Figure 3-19). In winters with relatively high numbers of marine birds or with relatively low adult herring biomass, as much as 10% (1864 t) of the adult biomass can be removed by avian predators (Figure 3-20).

Common murre, the most abundant bird during winter in PWS, is also the predominant avian predator on herring. In 8 of the 10 winters murre consumed the most adult herring and for all 10 winters, murre were the largest consumer of juvenile herring (Figure 3-19). Common murre exhibits dramatic inter-annual variation in abundance in PWS which affects its impact on the herring population.

Among the other marine bird species, glaucous-winged gull was the second largest consumer of juvenile herring during all winters. Pelagic cormorant and common loon were each the largest consumer of adult herring during one of the 10 winters examined.

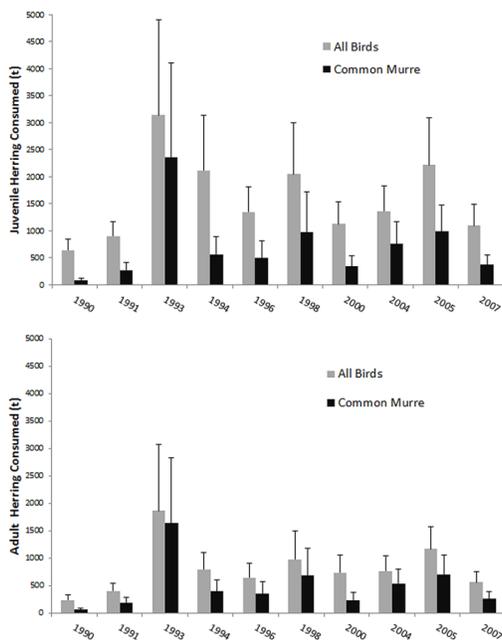


Figure 3-19 Winter consumption of juvenile herring (above) and adult herring (below) by all marine birds compared with common murre (including unidentified murre) as estimated from Monte Carlo simulations. Winter = 15 November through 15 March; bars = mean herring consumption; error bars = ± 1 sd. Year on the x-axis corresponds to the previous-present year's winter (e.g., 1994 refers to winter 1993 – 1994). No bird population estimates were available for 1992, 1995, 1997, 1999, 2001-2003, and 2006. From: Bishop et al., *Fisheries Oceanography*, 2015.

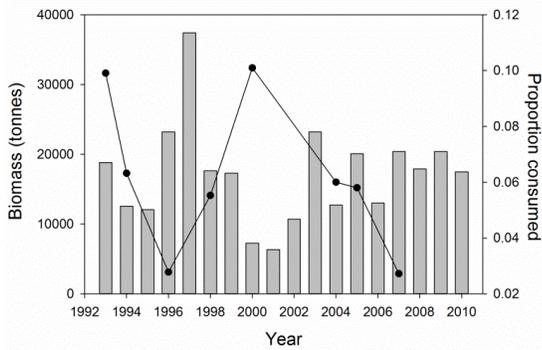


Figure 3-20 Estimated proportion of adult herring biomass consumed by marine birds (dots) for 8 survey years compared to available adult herring biomass (bars). Adult biomass estimates for 1993-2009 taken from Thorne and Thomas, 2008, 2011; biomass estimate for 2010 from R. Thorne, Prince William Sound Science Center, USA, pers. comm.). From: Bishop et al., *Fisheries Oceanography*, 2015.

Temporal Patterns & Winter Habitat Associations (based on Dawson et al. in press and current analyses by Stocking, Bishop and Arab)

We examined temporal patterns in density and distribution across winter for three of the most abundant seabird species during winter in PWS: common murre, marbled murrelet, and black-legged kittiwake. Consistent patterns were observed for all three species. Common murre and marbled murrelet both increased in density from early to midwinter. Between mid and late winter, murrelets decreased while murres increased in density. Black-legged kittiwake decreased to extremely low numbers during January surveys, increasing again in March (Figure 3-21).

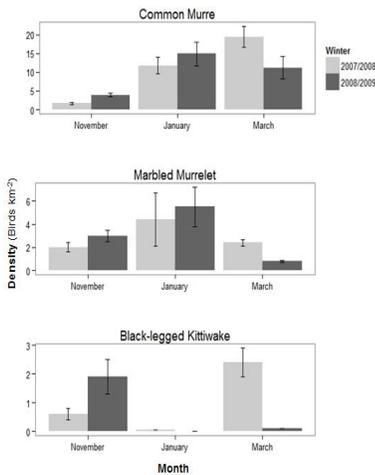


Figure 3-21 Mean (+ se) densities (birds km⁻²) in PWS during two consecutive seasons.

For common murre and marbled murrelet, we modeled fine scale habitat associations (1 km²) through the winter using a two-stage hurdle model (Zuur et al. 2012). Our results suggest that winter storms influenced murre and murrelet distributions, particularly in midwinter when temperatures were lowest and storms more frequent. PWS provides far more sheltered waters than the adjacent GOA and for both species we observed highest densities in protected waters during January. Our models showed that common murre favored relatively protected waters while marbled murrelet favored inside bays and passages (which make up 45% of semi-protected waters) and areas of higher sea surface temperatures.

A major assumption of the hurdle model used in Dawson et al. is that all zeros are instances of absence, i.e. they are “true zeros”. Detection is not a perfect process, particularly in the case of sampling animals; therefore, the probability of detection given presence is nearly always <1. In order to incorporate imperfect detection into our estimates of occupancy and relative abundance, future analyses will use zero-inflated Poisson (ZIP) models.

Our exploratory analyses using the ZIP models found that of the detection covariates, glare is significantly associated with the probability of an excess zero for most species groups (Table 3-6) and is a significant predictor of all groups’ count distributions. Bin (distance from the observer) is also consistently significant in explaining the probability of excess zeros across species groups and is significant in the count portion of the model for most groups. Our exploratory analyses also showed that of the temporal covariates, the variables winter (survey year) and day of the season were consistently significant in driving bird distributions. Of the environment-derived covariates, the variable marine habitat type was significant in nearly all cases. Distance to shore, SST, bathymetry, and slope were not consistent across species groups, likely expressing complicated or non-linear relationships with bird distributions. Spatial variables latitude and longitude were significant for most species groups.

Table 3-6 Zero-inflated Poisson model: zeros. Winter marine bird distribution in Prince William Sound, Alaska, 2007-2014. Sign (+/-) indicates coefficient of effect; a blank indicates not significant ($\alpha=0.05$). Categorical variables have an estimate for each level, and significance is indicated with \pm . Below the double line are variables that might be expected to influence detection probability, not explicitly estimable for these data.

Covariate	Murrelet	Murre	Cormorant	Loon	Merganser	LG Gull	SM Gull	Kittiwake
Distance to Shore		-			+	-	+	+
SST	+		+	-	+	+		-
Bathymetry	-		-	-		+	+	+
Slope				-		-	+	+
Longitude		-	+	-		-	+	
Latitude		+	-			+	-	-
Day	+	-	+		+	+	+	+
Exposure		\pm	\pm			\pm		\pm
Marine Habitat	\pm	\pm	\pm	\pm		\pm	\pm	\pm
Winter	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm
Bin	\pm	\pm	\pm	\pm	\pm	\pm	\pm	\pm
Glare	\pm	\pm	\pm	\pm			\pm	\pm

Wintering Marine Bird Assemblages in PWS Bays (based on Bishop and Kuletz, manuscript in prep.)

Across five winters, more than 10,100 birds representing 31 species were recorded on transects in survey bays. Common murre was the most abundant species, comprising 33.5% (n=3,392) of all observations, followed by pelagic cormorant (8.7%), long-tailed duck (8.0%), glaucous-winged gull (7.3%) and marbled murrelet (6.3%). Our surveys most likely underestimated winter waterfowl densities because the transect design was primarily pelagic. In southeast Alaska, aerial surveys showed that >90% of winter ducks occurred within 0.2 km of shore (Conant et al. 1988).

Four of the 11 marine bird groups showed significant differences between November and March densities (Table 3-7). Marbled murrelet, large gulls (glaucous-winged and herring gulls), and small gulls (mew and Bonaparte's gulls) were found in the bays in significantly larger numbers during November compared to March. Common murre were more abundant in bays during March surveys compared to November.

Multivariate analysis indicated that bird assemblages varied significantly between November and March surveys (Figure 3-22). The analyses identified densities of two species groups contributing $\geq 10\%$ to dissimilarities: common murre (22%) and marbled murrelet (10%).

Our results suggest that by late winter the less exposed bays of PWS provide a favorable environment for the common murre. In addition, the pre-spawn movements of large schools of adult herring, from deeper to more shallow waters during March, may be providing important foraging opportunities for common murre in bays.

Table 3-7 Mean density (\bar{x} + se) per km² of marine bird groups in selected PWS bays, November 2007 - March 2012. All groups recorded a minimum density of 0 at least once during November and March. Significant differences in densities between survey months are bold (Mann-Whitney-Wilcoxon rank test).

Species group	November		March		p
	\bar{x} (se)	max	\bar{x} (se)	max	
Loon	2.08 (0.61)	14.32	1.67 (0.64)	20.08	0.19
Grebe	0.75 (0.15)	2.92	1.22 (0.25)	4.91	0.29
Cormorant	1.26 (0.25)	4.86	5.85 (3.32)	116.58	0.25
Merganser	1.39 (0.33)	6.89	2.39 (0.65)	15.52	0.63
Large gull	3.68 (1.51)	49.16	1.27 (0.32)	9.31	<0.01
Small gull	2.19 (0.49)	12.68	0.99 (0.41)	14.31	0.02
Black-legged Kittiwake	1.86 (0.56)	12.8	1.19 (0.46)	11.26	0.18
Common Murre	1.94 (0.51)	9.53	20.99 (4.20)	95.12	<0.01
Marbled Murrelet	3.63 (0.86)	17.64	1.32 (0.33)	7.63	0.02
Shallow diving waterfowl ^a	3.90 (1.34)	29.62	1.74 (0.79)	24.02	0.37
Deep diving waterfowl ^b	1.16 (0.33)	6.41	5.53 (3.78)	132.75	0.61

^aShallow diving waterfowl = bufflehead, harlequin duck, Barrow's and common goldeneyes.

^bDeep diving waterfowl = long-tailed duck, white-winged and surf scoter.

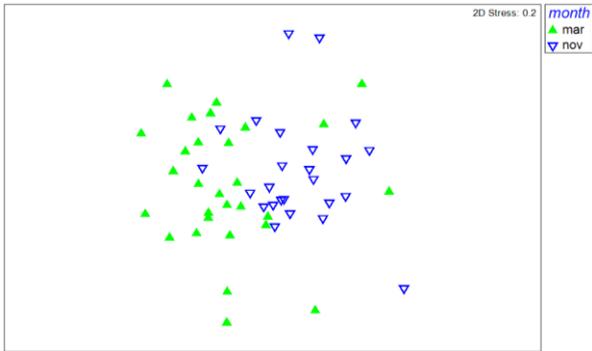


Figure 3-22. Non-metric multidimensional scaling (nMDS) ordinations of PWS survey bays based on marine bird assemblage and abundance data from November (open triangles) and March (closed triangles) surveys in the Prince William Sound. ANOSIM global $R=0.236$, $p<0.001$

Critical marine habitats used by seabirds during late fall and winter

Based on surveys conducted the past seven winters we have identified areas of high marine bird concentrations (Figure 3-23). Notably, northeast Prince William Sound, Montague Strait, and the southwest Passages are areas where Humpback Whales concentrate. Similarly, Montague Strait is a known hotspot for Killer Whales. This suggests that in these areas environmental drivers such as currents and nutrients are creating persistent, favorable foraging conditions for marine birds and marine mammals.

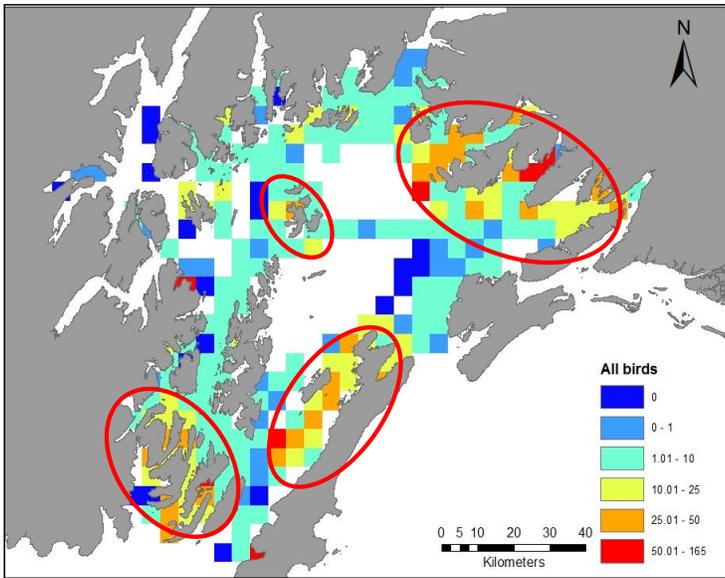


Figure 3-23 Average densities observed on fall/winter surveys within a 5 km x 5 km grid. November 2007 to March 2014, n = 27 surveys. White = not surveyed. Dark blue = surveyed but no birds observed

Summary

Management activities, including response to natural or anthropogenic perturbations (e.g. oil spill), or damage assessment arising from perturbations, need to take into account (a) the importance of herring for marine birds; and, (b) the seasonal variation in abundance and distribution in PWS marine birds. Our bioenergetics simulation model results suggest that in addition to herring being a critical food resource for marine birds, predation by marine birds may have an important top-down effect on herring populations. Our surveys demonstrate that the nonbreeding season cannot be characterized as a single time period. Densities of black-legged kittiwake, common murre, and marbled murrelet in PWS all vary significantly between November, January, and March, suggesting that multiple surveys are required to quantify wintering populations and understand changes in seabird distribution. Importantly, our results also suggest that historic surveys conducted across PWS in March (as in McKnight et al. 2006) have missed the winter peak in abundance for three abundant winter species: marbled murrelet, glaucous-winged gull, and mew gull thus underestimating the importance of PWS as a wintering habitat. Hurdle models of habitat associations for two of the most abundant winter species showed that common murre favored relatively protected waters while marbled murrelet favored inside bays and passages and areas of higher sea surface temperatures. These results suggest that winter storms influenced murre and murrelet distributions, particularly in midwinter when temperatures were lowest and storms in the Gulf of Alaska more frequent. Our exploratory ZIP models have identified variables that consistently appeared in our exploratory analyses, recognizing that further attention will be paid to quantify and implication of the effects once spatial autocorrelation is explicitly addressed and model selection performed.

Future Recommendations

Continue characterizing long-term variability and population trends in PWS marine birds during the nonbreeding season. Conduct annual fall through winter surveys to monitor species distribution and abundance. These marine bird surveys will provide the baseline data needed to identify change, relate the change to environmental features, and ultimately model the impacts of that change.

Ships of opportunity provide a cost-effective alternative, allowing broad examination of marine bird distribution trends in PWS. We will continue to identify “host” surveys with consistent routes, (i.e. multiple years of funding), in order to maximize inference across winters. If a specific host platform disappears and there is a gap in timing or coverage, supplemental funding should be provided to insure continued coverage.

This long-term dataset can illustrate changes in marine bird distribution across time and space relative to environmental characteristics. From this point, we will proceed with analyses that explicitly include spatio-temporal autocorrelation. We can then generate predictive surfaces of relative abundance for species groups across PWS. Trends could be indicative of variations in other parts of the ecosystem (e.g. oceanic drivers, forage fish availability), complementing findings of other EVOS Gulf Watch or Herring projects.

Conduct integrated hotspot monitoring to characterize multi-species predator prey aggregations. We have identified a few key areas where pelagic components including marine birds, forage fish, and whales overlap in time and space, (one example, Montague Strait during September). Future efforts should also integrate environmental conditions into this monitoring.

References

- Batten, S.D., K.D. Hyrenbach, W.J. Sydeman, K.H. Morgan, M.F. Henry, P.P.Y. Yen, and D.W. Welch. 2006. Characterising meso-marine ecosystems of the North Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography* 53: 270-290.
- Bishop, M.A., J.T. Watson, K. Kuletz and T. Morgan. 2015. Pacific herring consumption by marine birds during winter in Prince William Sound, Alaska. *Fisheries Oceanography* 24(1) 1-13.
- Bishop, M.A., and K.J. Kuletz. *In prep.* Winter marine bird assemblages in bays of southcentral Alaska.
- Clarke, K. R., & R.M. Warwick. 2001. Change in marine communities: an approach to statistical analysis and interpretation. <http://www.opengrey.eu/item/display/10068/595716>.
- Conant, B., King, J. G., Trapp, J. L., & Hodges, J. I. (1988). Estimating populations of ducks wintering in southeast Alaska. *Waterfowl in Winter (MW Weller, Ed.)*. University of Minnesota Press, Minneapolis, 541-551.
- Dawson, N.M., M.A. Bishop, K.J. Kuletz, and A.F. Zuur. *In press.* Using ships of opportunity to assess winter habitat associations of seabirds in subarctic coastal Alaska. *Northwest Science*.
- Kuletz, K.J., E.A. Labunski, M. Renner, and D. Irons. 2008. The North Pacific pelagic seabird observer program. North Pacific Research Board Final Report. Project 637. 88 pp.
- McKnight, A., K. M. Sullivan, D. B. Irons, S. W. Stephensen, and S. Howlin. 2006. Marine bird and sea otter population abundance of Prince William Sound, Alaska: trends following the T/V Exxon Valdez Oil Spill, 1989-2005. Anchorage, Alaska: Exxon Valdez Oil Spill Trustee Council.
- Thorne, R. E. and Thomas, G.L. 2008. Herring and the "Exxon Valdez" oil spill: an investigation into historical data conflicts. *ICES Journal of Marine Science* 65: 44-50.
- Thorne, R. E. and Thomas, G.L. 2011. The role of fishery independent data. In: *Fisheries Management*. J. S. Intilli (ed.) Hauppauge, NY: Nova Science Publishers, pp. 121-138.
- US Fish and Wildlife Service. 2007. North Pacific pelagic seabird observer program observers manual, inshore/small vessel. Protocol manual. US Fish and Wildlife Service, Migratory Bird Management Nongame Program, Anchorage, Alaska.
- Zuur A. F., N. Dawson, M. A. Bishop, K. Kuletz, A. A. Saveliev, and E. N. Ieno. 2012. Two-stage GAMM applied to zero inflated common murre density data. In A. F. Zuur, A. A. Saveliev and E. N. Ieno (editors), *Inflated and Generalized Linear Mixed Models with R*. Highland Statistics Ltd. Newburgh, United Kingdom. Pp. 149-182.

Chapter 3-Appendix 1: Summary of marine birds projects in the Gulf Watch Alaska region

Jessica Couture, National Center for Ecological Analysis and Synthesis, with contributions from the Gulf Watch Alaska Marine Birds working group: Kathy Kuletz, Daniel Esler, Mary Anne Bishop, Heather Coletti, Mayumi Arimitsu, David Irons, Tuula Hollmen, Angela Doroff, John Piatt, Robert Kaler, Thomas Dean, and Mandy Lindeberg

A variety of marine bird monitoring efforts have been conducted in the northern Gulf of Alaska, extending from the coastal areas of Katmai, into Lower Cook Inlet, the Kenai Fjords, Prince William Sound, and the continental shelf south of the Kenai Peninsula (Figure 3-24). The number of projects has varied among sub-regions of the northern Gulf, as well as among years (Figure 3-25), with the most consistent effort in Prince William Sound and the GOA shelf (via the Seward Line).

The projects are summarized in Table 3-8 and include information on marine bird abundance and productivity trends in the northern Gulf of Alaska. The projects include historic (pre-2000), recently completed, and ongoing efforts. The data from these projects will be used in future synthesis efforts and are currently, or will soon be, available for public access. The majority of these data are archived in either the Gulf Watch Alaska Data Portal (<http://portal.aaos.org/gulf-of-alaska.php>) or the Gulf of Alaska Historic Data Portal (<https://GOA.nceas.ucsb.edu/>). Projects have been funded by different entities including: the Exxon Valdez Oil Spill Trustee Council (EVOSTC), US Fish and Wildlife Service (USFWS), University of Alaska, Fairbanks (UAF), the National Park Service (NPS), the National Oceanic and Atmospheric Administration (NOAA), the Kachemak Bay Research Reserve (KBRR), and the North Pacific Research Board (NPRB).

These tables are meant to serve as general summaries of all of the projects in the Gulf Watch region. For details on methods or permission to access the data, please search the data portals listed above and contact the principal investigators involved. Project status codes define if the project is ongoing (O), was completed recently (C, since 2000), or is comprised of historic data (H, pre-2000).

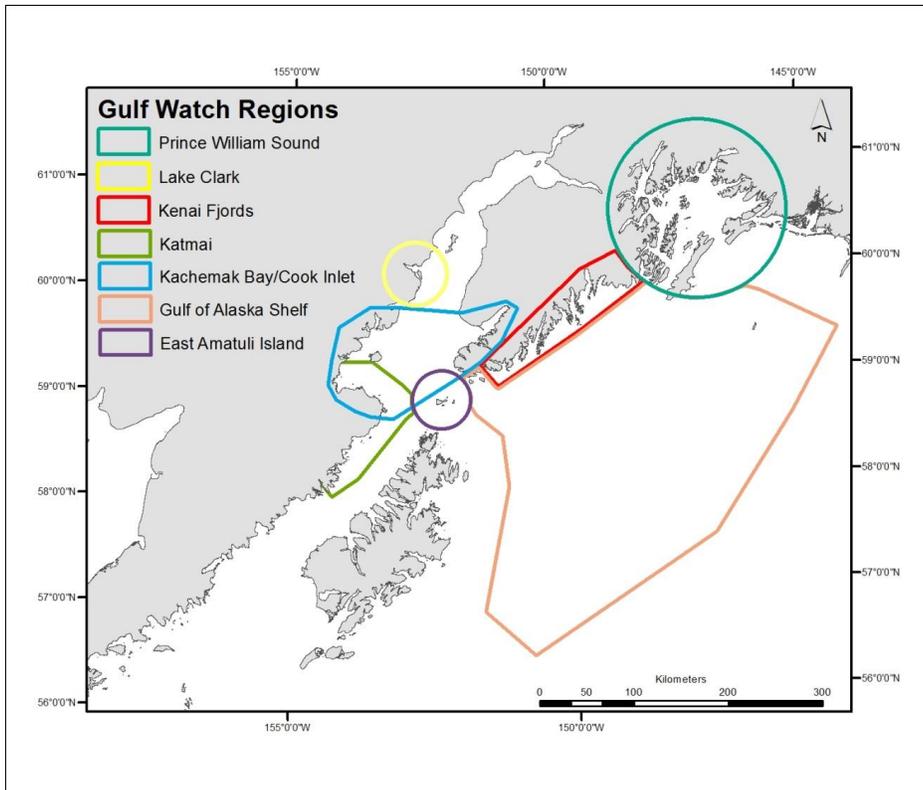


Figure 3-24. General sampling regions for marine bird projects in the northern Gulf of Alaska. The colors representing location boundaries correspond to the projects in Figure 2

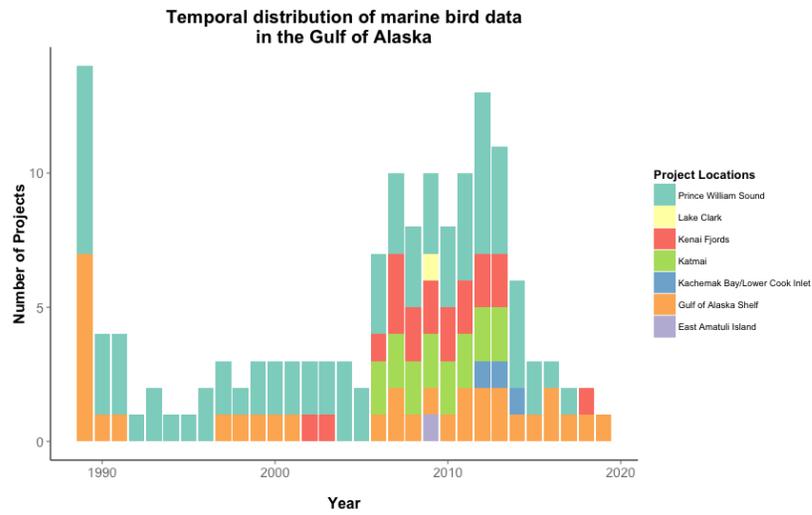


Figure 3-25. Temporal distribution of marine bird data in the Gulf of Alaska. Colors represent locations of the projects and correspond to regions mapped in Figure 1. Data beyond 2014 have been funded for continued research.

Table 3-8. Marine bird projects in the northern Gulf of Alaska region that include abundance and productivity trend information. This list is not intended to incorporate all marine bird research and monitoring in the northern Gulf of Alaska, but rather describes the primary data sets that could be used to evaluate trends in abundance, distribution, or productivity.

Region	Area	Years	Months	PIs & collaborators	Primary Agency	Funding	Project	Objectives	Ancillary information
Alaska NW GOA	Katmai	2006-2013	July	Coletti, Ballachee, Esler	NPS, USGS	NPS, EVOSTC	Black Oystertacher monitoring	Abundance trends (nesting densities), productivity trends (nest productivity)	Relate changes in diet composition to intertidal invertebrate studies; predator/prey dynamics
	Kenai Fjords	2007-2013	June						
	West PWS	2012-2013	May / June						
Alaska NW GOA	Lake Clark Katmai Kenai Fjords	2009 2006-2013 2007-2013	May July June	Coletti, Ballachee, Esler	NPS, USGS	NPS, EVOSTC	Marine bird and Mammal Surveys	Abundance trends	Distribution for all marine birds
GOA	CPR, Canada to Japan	2002-2006	Jan-Dec	Batten		EVOSTC	Marine Bird and mammal observations in the North Pacific Ocean	Abundance and distribution	Species composition and distribution relative to concurrent oceanographic and plankton data
GOA	Middleton Island	~1975-2014	May - Aug	Hatch	USGS; ISRC (current)	USGS, NFWF, USFWS	Middleton Island studies	Abundance trends, Productivity trends	Productivity relative to diet; long-term seabird diet data
GOA	North Gulf of AK	1997-2001	~ Sept-Dec	Day	ABR	Exxon-Mobil	Marine bird and mammal winter surveys in offshore waters	Abundance and distribution	Distribution relative to concurrent oceanographic and prey data
GOA	Northern GOA, SEAK	2011-2013	April, June-Aug	Slater	USFWS	NPRB	GOIERP surveys of marine birds	Abundance and distribution	Distribution relative to concurrent oceanographic and prey data
GOA	Resurrection Bay	2006-2007 2011-2015	Apr-Jul; monthly	Hollmen	ASLC	NPS, ASLC	Nearshore marine bird surveys	Abundance trends (annual and seasonal), productivity trends (via age ratios)	Distribution and habitat use of nearshore marine birds (monthly surveys started Sept 2011)
GOA	Seward Line (& Homer to W/PWS)	2007-2013 (sporadic); 2014-19	May & Sept	Kuletz, Hopcroft	USFWS, UAF	USFWS, NPRB	Marine bird surveys in the northern GOA	Abundance trends	Marine bird distribution relative to marine conditions
Kenai Peninsula	East Amatuli Island	1999	June-Sept	O'Meara	Pratt Museum, USFWS	EVOSTC	East Amatuli Island Common Murre video link	Productivity trends	Test remote video surveillance of nesting Common Murres
Kenai Peninsula	Kenai Fjords	2006-2008	May-Aug	Arimitsu, Piatt	USGS	NPS	Kittlitz's and Marbled Murrelet surveys	Abundance trends	Assess productivity based on at-sea surveys, contrast marine habitats used by two murrelet species
Kodiak	Bays, shoreline	1970s to present (sporadic)	mainly winter	Kodiak Refuge personnel	USFWS	USFWS	Marine bird surveys in Kodiak area	Abundance trends	Marine bird distribution in winter
Lower Cook Inlet	Kachemak Bay	1999-2003	Feb-March	Rosenberg, Petula	ADFG	ADFG	Winter skiff surveys of sea ducks in Kachemak Bay	Abundance trends, Productivity trends (via age ratios)	Distribution and habitat use of sea ducks
Lower Cook Inlet	Cook Inlet & Kachemak Bay	1995-1999	June-Aug	Piatt, Abookire, Speckman	USGS, AMNWR	MMS, EVOSTC	Cook Inlet Seabird and Forage Fish Study	Abundance trends, Productivity trends (colony-based studies)	Abundance and distribution of all marine birds via at sea surveys; productivity & diet studies at 3 colonies for selected species
Lower Cook Inlet	Lower Cook Inlet	2012-2015	Feb, Apr, Jul, Oct	Kuletz, Doroff, Holderied	USFWS, KBRR, NOAA	USFWS, BOEM	Marine bird and Mammal surveys	Abundance trends and distribution	Estimates of relative abundance and distribution of all marine birds relative to concurrent oceanographic studies
Lower Cook Inlet	Kachemak Bay	2005-2007 2011	July	Kuletz	USFWS	USFWS, ADFG	Marine bird and Mammal surveys	Abundance trends and distribution	Abundance, distribution and habitat use of all marine birds, with a focus on Brachyramphus murrelets; concurrent CTD data collected most surveys.

PWS	Naked, Storey, Peak, Smith, Fool islands	2013-2018	winter/ spring; May-Aug	Kaler, Irons	USFWS	EVOS, NFWF	Pigeon Guillemot Restoration	Abundance trends, productivity trends	Remove invasive mink for seabird recovery; determine relationship between diet and Pigeon Guillemot productivity
PWS	Naked, Storey, Peak, Smith, islands	1995-2000	May - Aug	Hayes, Kuletz, Golet, Irons	USFWS	EVOSTC	Factors affecting Pigeon Guillemot nesting in PWS	Abundance trends, Productivity trends	Determine relationship between predation, diet, and Pigeon Guillemot productivity
PWS	PWS - bays and pelagic	2011-2016	Oct, Nov Dec, Feb	Bishop	PWSSC	EVOSTC Gulf Watch	Fall and winter monitoring of marine birds	Abundance trends and distribution	Distribution in relation to environmental variables (used repeated transits on ships of opportunity)
PWS	17 Selected fjords	2001, 2004, 2009	June-Aug	Kuletz, Stephensen, Allyn	USFWS	USFWS, NFWF	Abundance, distribution and habitat use of Kittlitz's Murrelet	Abundance trends and distribution	Abundance and distribution of all marine birds in 17 selected bays and fjords of PWS; seasonal changes in abundance and distribution
PWS	PWS – all areas	2012-2013	July-Aug	Arimitsu, Piatt	USGS	EVOSTC	Long-term monitoring of forage fish (with concurrent seabird surveys)	Abundance and distribution of forage fish	concurrent data on marine bird density (systematically placed hydroacoustic transects)
PWS	PWS - Shoreline & pelagic	1989-2014 1990-2005	July March	Kaler, Irons, Kuletz	USFWS	EVOSTC	PWS marine bird surveys	Abundance trends (using randomly selected transects)	Distribution and habitat use of all species
PWS	PWS shorelines	1993	June - Aug	Cody	USFWS	EVOSTC	Census of Pigeon Guillemot colonies in PWS	Abundance and distribution	Baseline for future monitoring efforts; ascertained the relative importance of Naked Is. group to PWS Pigeon Guillemot population
PWS	PWS shorelines	~1980s - 2015	June, Aug	Irons	USFWS	USFWS	Abundance and productivity of black-legged kittiwakes in PWS	Abundance trends, Productivity trends	Long-term data on kittiwake colony distribution and productivity
PWS	PWS shorelines	1995-2009	Nov, March	Rosenberg, Petrala	ADFG	EVOSTC	Harlequin Duck surveys in PWS	Abundance trends, Productivity trends (via age ratios)	Distribution and habitat use of Harlequin Ducks
PWS	Western PWS	1996 - 1997	Nov, Feb	Esler	USGS	EVOSTC	Fall and winter nearshore surveys of marine birds	Abundance and distribution	Habitat use of nearshore marine birds in late fall and winter

Chapter 4 VARIABILITY WITHIN NEARSHORE ECOSYSTEMS OF THE GULF OF ALASKA

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Introduction and Background

Nearshore marine habitats, which represent the interface among air, land and sea, form a critical component of the Gulf of Alaska (GOA) ecosystem. As an interface, the nearshore facilitates transfer of water, nutrients and biota between terrestrial and oceanic systems, creating zones of high productivity. The nearshore provides a variety of ecosystem services, including (1) nursery grounds for a wide variety of marine invertebrates and fishes (e.g., crabs, salmon, and herring), (2) nesting and pupping habitats for many pelagic marine predators (e.g., sea bird nesting colonies and pinniped rookeries), (3) important feeding habitats for high trophic level pelagic predators (e.g., killer whales), (4) habitat for resident nearshore species (including sea otters, harbor seals, shorebirds, sea ducks, nearshore fishes, and marine invertebrates), many of which are important sources of commercial and subsistence harvests, and (5) recreational, commercial and subsistence opportunities for human populations (Figure 4-1). The canopy forming kelps and eel grass beds found in the nearshore provide primary production and structure to nursery habitats, and also can dissipate wave energy thus reducing coastal erosion, and serve as a carbon “sink” capable of storing substantial amounts of atmospheric CO₂ (Wilmers et al. 2012).

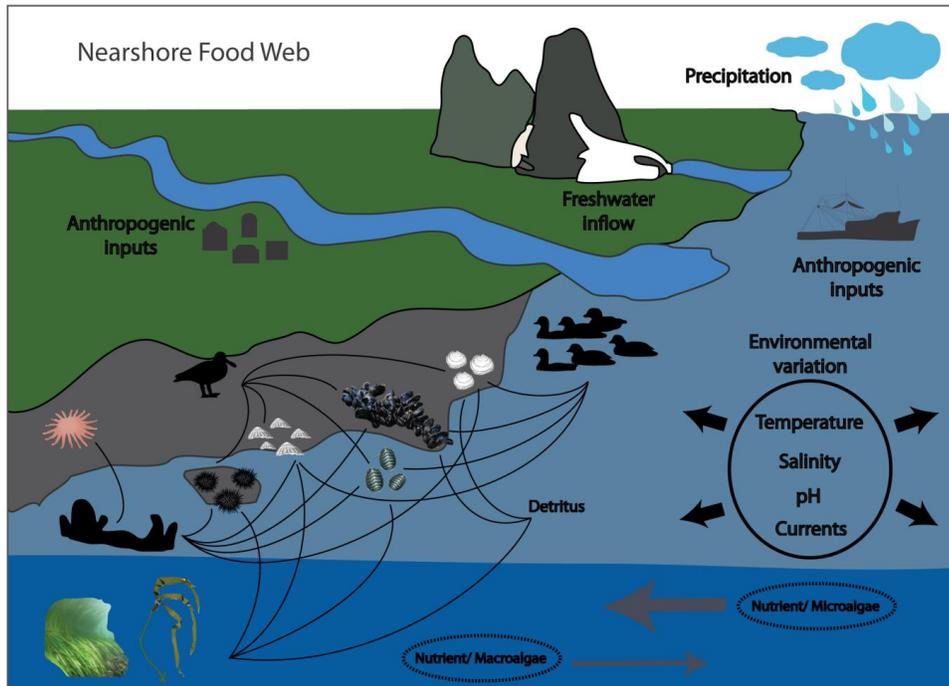


Figure 4-1. Conceptual model illustrating ecological connections within the nearshore food web.

Nearshore ecosystems are sensitive to natural and human disturbances on a variety of temporal and spatial scales, originating from any of the three major interfacing systems (e.g., pelagic toxic algal blooms and leaching of contaminants from watersheds). As with all marine systems, they face tremendous challenges associated with increased human impacts, including climate change (Crain et al. 2009, Hoegh-Guldberg and Bruno 2010) for which some consequences (e.g., ocean acidification) are anticipated to be far reaching and more severe at higher latitudes (Fabry et al. 2009).

Because many organisms in the nearshore are sessile or have limited home ranges, they are good candidates as indicators linked to sources of change. As a result of long-term experimental and monitoring work, we have a comparatively thorough understanding of mechanistic links between many nearshore consumers and their prey that facilitates understanding causes of change. Thus, monitoring of nearshore resources at appropriate spatial scales and over longer term periods affords opportunities to detect both regional and relatively localized causes of change and distinguish human-induced from natural changes, providing a basis for development of policies to reduce human impacts. In the GOA, monitoring of nearshore resources has been of particular importance in the past several decades, because it was the habitat most impacted by the 1989 *Exxon Valdez* oil spill (EVOS), and has been a repository for lingering oil linked to protracted injury to resident species (see Chapter 5 of this report). As a result of support for EVOS studies over the past 25 years, there are now a substantial number of long-term data sets on nearshore resources that form a valuable foundation for continued monitoring efforts to help us

understand how large-scale perturbations, including EVOS, affect recovery and function of these ecosystems (Esler 2013, Ballachey et al. 2014, Bodkin et al. 2014).

Historical and Ongoing Nearshore Monitoring in the Gulf of Alaska

In the early 2000s, a comprehensive monitoring plan for the nearshore marine ecosystem in the GOA was developed (Dean and Bodkin 2006). The framework for monitoring in the nearshore included sampling of a variety of specified biological and physical parameters (e.g. abundance and growth of intertidal organisms, abundance of selected birds and marine mammals, water quality) within specified areas across the GOA, selected to enhance our ability to detect change from a variety of sources. The monitoring plan was adopted by the National Park Service Southwest Alaska Network for their Vital Signs Long-term Monitoring Program (Bennett et al. 2006), and implemented in Katmai National Park and Preserve (KATM) in 2006 and Kenai Fjords National Park (KEFJ) in 2007. The plan also was implemented in western Prince William Sound (WPWS) in 2007, and again starting in 2010. In 2012, when the Gulf Watch Alaska (GWA) project was established, these ongoing nearshore monitoring efforts in WPWS, KATM, and KEFJ were assembled under the Nearshore component of the GWA program. At that time, additional monitoring areas in northern and eastern PWS (NPWS and EPWS) and in Kachemak Bay (KBAY, already the site of long-term nearshore studies by UAF) were incorporated into the overall Nearshore monitoring component of GWA, forming a total of 6 study areas. This distribution of monitoring areas across the GOA provides a broad geographical scale which, when combined with the acquisition of historic data sets, greatly increases our ability to detect and assign cause to differences among areas and over time. A list of metrics that are currently being monitored on an annual basis is provided in Table 1, below (note: EPWS and NPWS are being monitored only in alternate years). Detail on methods for data collection are presented in the protocols of marine nearshore ecosystem monitoring in the Gulf of Alaska (Dean et al. 2014).

Complexities Contributing to Variability of Nearshore Ecosystems in the Gulf of Alaska

Ecological processes and physical conditions are widely recognized to affect the structure, composition and function of nearshore communities. As part of GWA, we are working to assess influences at multiple scales of various physical and biological drivers potentially capable of causing change in nearshore ecosystems. At the local scale, we are examining factors including region, stratum (tide height), and static factors such as exposure, fetch, freshwater input, tidewater glacial presence, and substrate (see Konar et al., this report). At broader scales of space and time, longer term monitoring and data have increased awareness of drivers such as the Pacific Decadal Oscillation (PDO), El Niño/Southern Oscillation (ENSO), and North Pacific Gyre Oscillation (NPGO), and we are just starting to consider whether impacts of these drivers can be detected on nearshore populations and communities in the GOA (see Monson et al., this report). Additional forces with even greater unknowns are those associated with climate change (e.g., warming waters and ocean acidification).

Our ability to monitor the nearshore ecosystem, and detect short to long-term and local to regional scale change in biological resources and their productivity, is based on several key aspects of the GWA program. First, we are evaluating metrics on a relatively large number of species, including vertebrates and invertebrates at different trophic levels, as well as marine plants and algae, all of which are important components of nearshore communities. Second, we are monitoring this suite of metrics at study areas selected to represent a large spatial scale across the GOA, allowing for differentiation of local versus regional change and providing insight into the role of environmental drivers in structuring communities.

Third, we are accumulating long-term data sets on these nearshore species (in some cases, representing decades of information), which is essential if an ecosystem monitoring program is to be effective at identifying causes of change. Fourth, the Nearshore component of GWA is a truly integrated effort, not an assemblage of related and somewhat independent projects; this allows for consistency in overarching concepts, as well as in the performance of the monitoring and delivery of findings. In addition, we are working on the development of conceptual models related to the nearshore ecosystem, which will provide important insight into food webs and other factors influencing community structure as we continue with the monitoring program. We expect over time to integrate data from the “Environmental Drivers” and “Pelagic” GWA components to increase our understanding of the role that ocean and atmospheric derived factors influence nearshore ecosystems.

Nearshore Component Synthesis Products

For the Nearshore component, we present two synthesis products in this chapter: (a) Influence of static habitat attributes on local and regional biological variability in rocky intertidal communities of the northern Gulf of Alaska, and (b) Inter-annual and spatial variation in Pacific blue mussels (*Mytilus trossulus*) in the Gulf of Alaska. In the first analysis, Konar et al. (this chapter) found that variation in biological communities in the central GOA is associated with stratum, region and static attributes. The biological communities in the KBAY and KATM regions formed fairly distinct groups, while sites from PWS and KEFJ regions strongly overlapped. These findings indicate there are additional regional drivers, either static or dynamic, that have not yet been examined and may be specific to regions with the GOA and. Further understanding the importance of static and dynamic drivers at the regional level is important for long-term monitoring of these communities, and also is applicable for management purposes in terms of damage assessment and climate change.

These are two examples, using subsets of data collected as part of the Nearshore component of GWA, that illustrate the value of having broad-scale and long-term datasets when evaluating change in marine ecosystems. We have many additional data streams for other metrics that will further contribute to our understanding of nearshore ecosystems in the Gulf of Alaska. Continuation of the Nearshore component will extend the timeline of data collection and hence increase the power to answer questions about sources and mechanisms of change.

List 4-1. List of metrics measured as part of the Nearshore monitoring program.

Metrics* are collected at 5 sites at each of 6 study areas: KATM, KBAY, KEFJ, WPWS, EPWS and NPWS. All sites are monitored on an annual basis except NPWS and EPWS, which are monitored every other year.

1. Rocky intertidal shoreline:

- % cover of various species (algae and sessile invertebrates) at tidal elevations of 0.5 and 1.5 MLLW
- *Lottia persona* (limpets) – mean size and density, at the upper tidal elevation
- *Nucella* spp. (sea snails) and *Katharina tunicata* (chiton) – densities, at 0.5 m and 1.5 m MLLW
- Sea star densities along a 100 m transect at the 0 tidal elevation
- Temperature

2. Mussel beds:

- Density of larger mussels ≥ 20 mm
 - Overall density of mussels
 - Area (m²) of mussel beds
3. Bivalves in soft sediments:
- Species composition
 - Density
 - Size distribution
4. Eelgrass beds:
- Proportion of area with eelgrass present
5. Marine bird and mammals surveys:
- Density and distribution of birds and mammals
6. Black oystercatchers:
- Density of active nests
 - Number of eggs and chicks / active nest
 - Species composition and size distribution of prey (shell remains) at nest sites
7. Sea otter foraging observations:
- Visual observations of foraging sea otters to quantify energy recovery rates through:
 - prey type
 - prey size
 - dive and surface times
 - proportion of successful dives
 - caloric recovery rates
8. Sea otter abundance:
- Aerial surveys to estimate abundance of sea otters
9. Sea otter mortality patterns:
- Annual collection of carcasses from shorelines to assess patterns of mortality, based on ages at death

*Metrics 5-9 are not collected at the extensive sites; and metric 8 is not collected annually. Bivalves in soft sediment sites in all areas are only sampled every other year to minimize effects from destructive sampling.

Nearshore Component: Considerations for Future Directions

- Continue broad-scale, long-term monitoring, largely as currently conducted; revise metrics and protocols based on the first 5-10 years of monitoring (although any changes must be highly justified, to avoid breakage of data streams).
- Enhance local-scale monitoring of key physical variables, considering the strong local structure of biological communities.
- Initiate directed research on important relationships and processes revealed in the first 5 years of monitoring, such as growth, recruitment, and population dynamics of benthic invertebrates and algae and performance of vertebrate consumers.

- Institute winter marine bird surveys directed at Gulf Watch Alaska Nearshore component study areas, including WPWS, Kenai Fjords, and Katmai National Parks.
- Support continuation of Resurrection Bay monthly marine bird surveys led by the Alaska SeaLife Center.
- Develop outreach products indicating the “State of the Nearshore” to be updated on an annual basis.

References

- Ballachey, B. E., D. H. Monson, G. G. Esslinger, K. Kloecker, J. Bodkin, L. Bowen, and A. K. Miles. 2014. 2013 update on sea otter studies to assess recovery from the 1989 Exxon Valdez oil spill, Prince William Sound, Alaska. U.S. Geological Survey.
- Bennett, A. J., W. L. Thompson, and D. C. Mortenson. 2006. Vital signs monitoring plan, Southwest Alaska Network Inventory and Monitoring Program. Anchorage, AK.
- Bodkin, J. L., D. Esler, S. D. Rice, C. O. Matkin, and B. E. Ballachey. 2014. The effects of spilled oil on coastal ecosystems: lessons from the “Exxon Valdez” spill. In: Coastal Conservation. Pages 311–346. B. Maslo and J. Lockwood, editors. Cambridge University Press.
- Crain, C. M., B. S. Halpern, M. W. Beck, and C. V Kappel. 2009. Understanding and managing human threats to the coastal marine environment. *Annals of the New York Academy of Sciences* 1162:39–62.
- Dean, T. A., and J. L. Bodkin. 2006. Sampling Protocol for the Nearshore Restoration and Ecosystem Monitoring (N-REM) Program (Nearshore Restoration and Ecosystem Monitoring Research Project G-050750), US Geological Survey, Alaska Science Center. Anchorage, AK.
- Dean, T. A., J. L. Bodkin, and H. A. Coletti. 2014. Protocol Narrative for Nearshore Marine Ecosystem Monitoring in the Gulf of Alaska: Version 1.1. Natural Resource Report NPS/SWAN/NRR - 2014/756. Fort Collins, Colorado.
- Esler, D. 2013. Long-term monitoring: lingering oil evaluating chronic exposure of harlequin ducks and sea otters to lingering “Exxon Valdez” oil in Western Prince William Sound, “Exxon Valdez” Oil Spill Trustee Council Restoration Project Final Report (Project 12120114-. Delta, British Columbia, Canada.
- Fabry, V., J. McClintock, J. Mathis, and J. Grebmeier. 2009. Ocean Acidification at High Latitudes: The Bellwether. *Oceanography* 22(4):160–171.
- Hoegh-Guldberg, O., and J. F. Bruno. 2010. The impact of climate change on the world’s marine ecosystems. *Science (New York, N.Y.)* 328(5985):1523–8.
- Wilmers, C. C., J. A. Estes, M. Edwards, K. L. Laidre, and B. Konar. 2012. Do trophic cascades affect the storage and flux of atmospheric carbon? An analysis of sea otters and kelp forests. *Frontiers in Ecology and the Environment* 10(8):409–415.

RESEARCH SUMMARY: PROJECT SUMMARY: INFLUENCE OF STATIC HABITAT ATTRIBUTES ON LOCAL AND REGIONAL BIOLOGICAL VARIABILITY IN ROCKY INTERTIDAL COMMUNITIES OF THE NORTHERN GULF OF ALASKA

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Purpose and problem

Intertidal communities naturally experience and are resilient to a large range of physical conditions. Some physical conditions are dynamic and fluctuate on various temporal scales (e.g., temperature, salinity, nutrients, etc.), while others are static (*sensu* Meager et al. 2011) and do not greatly fluctuate from year to year (e.g., substrate, slope, exposure, etc.). Although static attributes typically change minimally over time scales of at least years to decades, they can vary greatly among spatial scales of regions, local sites and even within a site (i.e., the various intertidal strata) and can influence biological community structure. We have previously documented that intertidal communities in the northern Gulf of Alaska vary with tidal stratum, as well as among sites and regions (Konar et al. 2009), but the specific role of static habitat attributes in driving these spatial differences is still unclear. It is important to assess how and on which spatial scales (regional, local, intertidal stratum) those static attributes structure intertidal communities if we are to isolate and understand the influence of more temporally variable attributes, especially in the context of changing climate conditions.

This paper seeks to determine how and on which spatial scales intertidal communities are structured by static habitat attributes. Specifically, we examine how mid and low intertidal communities at 31 sites in six regions across the northern Gulf of Alaska vary depending on their distance to freshwater, tidewater glacial presence, exposure, fetch, slope, and substrate type. As such, the three primary objectives of this study were to 1) assess mid and low intertidal community structure across sites and regions in the northern Gulf of Alaska, 2) describe the static habitat attributes at these same locations, and 3) determine on which spatial scales communities are structured by static habitat attributes. Once analyzed, these data were used to address our overarching hypothesis: Intertidal community structure across the northern Gulf of Alaska is more variable at the local scale compared to the regional scale because local species composition is a subset of the organisms that occur regionally, which is dictated by local static structural attributes.

Study area

We examined intertidal communities in six regions around the Gulf of Alaska (GOA) (**Error! Reference source not found.** In 2012, Western Prince William Sound (WPWS), Eastern Prince William Sound (EPWS), Kenai Fjords National Park (KEFJ), Katmai National Park and Preserve (KATM), and Kachemak Bay (KBAY) were sampled. In 2013, the same regions were sampled except that Northern Prince William Sound (NPWS) was sampled instead of EPWS. Prince William Sound (PWS), centered at approximately 60° N, 147° W, is a sub-arctic embayment having characteristics of a small inland sea with abundant fresh water inputs. Hinchinbrook, Hawkins, and Montague Islands serve as a barrier to the greater GOA. PWS is bounded by the Chugach Mountains on the east, north and west, and covers an area

of 8,800 km² containing many islands within its interior, and more than 3,200 km of complex shoreline (Cooney et al. 2001). Glaciated fjords dominate northern Prince William Sound (NPWS) with deep open water basins to >700 m depth occupying the central Sound. The tidal glacial influences of eastern Prince William Sound (EPWS) are less pronounced, leaving a coast generally characterized by sedimentary formations and nutrient-rich watersheds. Volcanic landforms dominate western Prince William Sound (WPWS) where production is driven by a portion of the Alaska Coastal Current siphoned off the GOA through Hinchinbrook Entrance and circulating back out through passages of WPWS (Montague Strait; Latouche, Elrington, Prince of Whales, and Bainbridge Passages (Gay and Vaughan 2001)). KEFJ (60° N, 150° W) is 2,700 km² and located along the southeastern side of the Kenai Peninsula in southcentral Alaska. The coast includes over 1,100 km of shoreline, and is characterized by fjords and offshore islands (Mundy 2005). Atop the Peninsula is the Harding Icefield, one of the largest ice caps in the US, which makes most of the Kenai Fjords watershed glacially fed. KBAY is located north of the Gulf of Alaska at 60° N and 151° W, with an area of 1,500 km² and 540 km of shoreline (Schoch and Chenelot 2004). The bay is a large estuary that can be divided into an inner and outer bay. The outer bay is largely free of glacial influence, while several points of glacial discharge enter the inner bay. KATM (59° N, 155° W) is located on the Alaska Peninsula, to the northwest of Kodiak and Shelikof Strait and also is influenced by glacial influx (Mundy 2005). The park and preserve is approximately 16,200 km² and has 795 km of coastline. Storms, wind mixing, and terrestrial inputs result in high productivity along the KATM coast. Storms, wind mixing, and terrestrial inputs result in high productivity along the KATM coast.

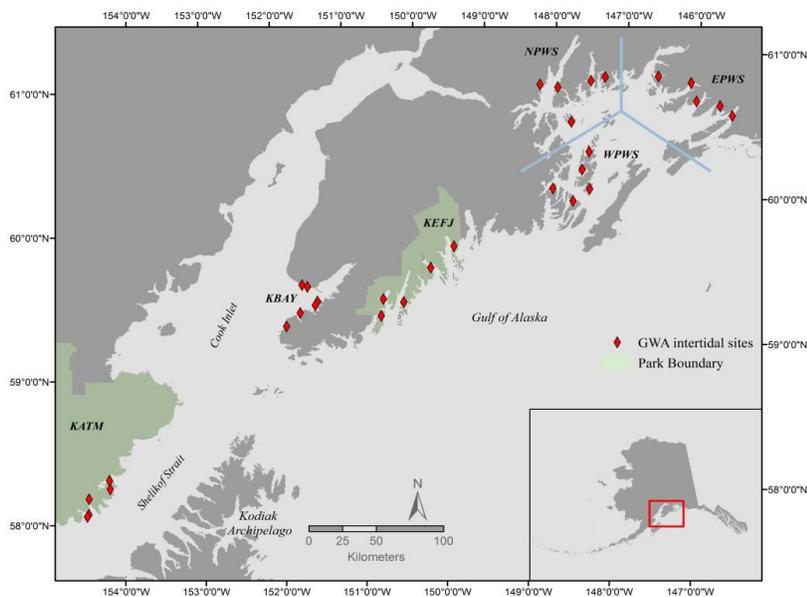


Figure 4-2. Figure 4 2. Map showing study sites within Northern Prince William Sound (NPWS), Western Prince William Sound (WPWS), Eastern Prince William Sound (EPWS), Kenai Fjords M(KEFJ), Kachemak Bay (KBAY), and Katmai (KATM).

Sampling generally followed Gulf Watch Alaska nearshore protocols (<http://portal.aaos.org/gulf-of-alaska.php#metadata/53c052b6-8874-46d1-b40a-acc615a3879a/project>). Five sites were sampled in each region (six in KBAY) in the mid and low intertidal zones (approximately from + 2.5 and + 1.5 m, respectively, relative to MLLW), except in 2012 in KBAY, when one site in that region was only sampled in the low intertidal. At each site, the intertidal community was visually quantified at randomly placed quadrats along a 50-m transect in both the mid and low tidal stratum for percent cover of sessile invertebrates and algae in one of two ways. At all sites except for those in KBAY, cover was determined within twelve 0.25 m² quadrats in each stratum, which were systematically positioned along the transects based on a random start point uniquely selected each year. Within quadrats, the presence of algae and sessile invertebrates was determined at 25 systematically placed points, and the percent cover was estimated based on the proportion of points occupied by each taxa. The presence of all taxa occurring within multiple layers was resolved by removing each subsequent layer after recording species. For the purposes of the present analysis, only data from the overstory kelp layer, if present, and the first, uppermost layer underneath kelp were used to make these data comparable to data from KBAY. In KBAY, percent cover of the overstory kelp layer, if present, and the top layer of sessile invertebrates and algae were visually estimated from ten randomly placed 1 m² quadrats along a 50-m transect. Data from the kelp layer and the underlying layer were combined and their abundances re-standardized to 100%.

The selected set of static habitat attributes for this analysis included distance to the nearest freshwater source, tidewater glacial presence, exposure, fetch, slope, and substrate type (i.e., percent of bedrock, boulder, cobble, gravel, mud/sand; categories according to the Wentworth scale). These specific attributes were chosen because of their potential influence on nearshore community structure (Zacharias and Roff 2001). Freshwater stream locations and tidewater glacier locations were obtained from the National Hydrography Dataset (NHD) from about the early 2000s, a comprehensive set of digital spatial data that includes marine and coastal information. For analysis, all data layers were converted into rasters. Using ArcGIS Spatial Analyst Cost Distance tool (ESRI, Redlands, CA), distances from sites to freshwater stream location and tidewater glacier presence within each region were calculated only across water bodies, excluding land masses. Raster data layers for glaciers, shoreline, freshwater streams, etc. were all based on an equal number and equal size of pixels or cells (50 m x 50 m cell size chosen) to standardize distance measures. We recognize that while the distance to a freshwater source and tidewater glacier presence are static elements, the discharge rates of these two sources are variable over seasonal and annual scales. These variables can be included in future analyses of the influence of dynamic variables. However, whether or not these sources were present and at what distance were still deemed important in the static habitat attribute setting.

Exposure was determined from the ShoreZone Alaska web site, where locations are classified based on the Biological Wave Exposure classification as protected, semi-protected, or semi-exposed

(<http://alaskafisheries.noaa.gov/mapping/DataDictionary/>). Fetch was calculated similar to Burrow et al. (2008) by creating vertices every 10° for 360° to a length of 200 km emanating from the center point of each study site. Vertices were clipped once a land mass was encountered. A sum of the remaining vertices' distances was used to calculate fetch. Two land resolutions, or buffers, were created to evaluate the effect of small rocks or islets on a particular site: 200 m and 5000 m. All land masses that fell within the buffers were erased for the respective distance fetch measurements. Slope was determined for each tidal stratum at each site in all regions by measuring the slope (in degrees) for every 1 m rise in elevation

at five equally-distanced points along a transect (at mid and low stratum). Slope for the low and mid strata were then calculated as the 0 to 1 m and 1 to 2 m rises, respectively, at each site and averaged for each site and stratum (mean slope). Substrate type was visually estimated as percent substrate cover (sand, gravel, cobble, boulders, bedrock) within each quadrat and the mean calculated for each stratum at each site.

Analyses

All statistical analyses were done in PRIMER v 7. All biological percent cover data were square root transformed, and a resemblance matrix created based on Bray-Curtis similarities. Data for structural habitat attributes were checked for multivariate normality using bivariate draftsman plots, square root transformed and then normalized to a common measurement scale. A resemblance matrix of similarities among all sample site pairs based on habitat attributes was then created using Euclidean distances.

Quantitative differences in biological community structures were examined between the two years, among the six regions, among the different sites within each region, and between the two strata. A four-factor mixed-model nested PERMANOVA was used, with year, region and stratum as fixed factors, and site nested within region as a random factor. The relative differences in biological communities between regions and sites were evaluated graphically with nMDS for each stratum separately. A CLUSTER analysis on each stratum was conducted on the static habitat attributes such that one of nine habitat clusters in the mid and eight clusters in the low was assigned to each site. These habitat clusters were then illustrated on the nMDS based on the biological communities to compare station groupings by habitat characteristics. A one-way ANOSIM based on the biological data ordered by habitat clusters was run on both the mid and low static attribute groupings to determine significant differences among the cluster groups. In addition, the overall relationships between the static habitat attributes and the biological communities for each stratum were evaluated using the BEST BIO-ENV routine and a subset of variables identified that maximized the rank correlations between these data. Lastly, the highest ranked static habitat attributes (from the BEST BIO-ENV routine) were overlaid as vectors on the biological site nMDS to assess which drivers best separate the biological site groupings.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Key findings

The highest variability in the intertidal community data was associated with stratum, followed by site, which was nested within region (Table 4-1, PERMANOVA). While region was also significant, it had a lower Pseudo-F value than either stratum or site. Year was not significant. Most of the variability in these data was explained by site (18.1%), region (11.7%) and the site by stratum interaction (11.7%), with only 37.7% being attributed to residuals (Table 4-2, variance estimates).

Table 4-1. PERMANOVA results testing differences in the biological data by year, region, stratum, and site (nested in region). Differences in the biological communities are based on Bray-Curtis similarities of square root transformed percent cover data. The largest pseudo-F values are associated with site and stratum.

Source	df	SS	MS	Pseudo-F	P(perm)
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year	1	10171	10171	2.1613	0.053
region	5	4.25E+05	85024	4.0437	0.001
stratum	1	1.44E+05	1.44E+05	19.735	0.001
site(region)	24	5.34E+05	22243	18.969	0.001
Ye x re**	3	19894	6631.5	1.3808	0.144
Ye x st	1	5787.5	5787.5	2.766	0.023
Re x st	5	64532	12906	1.6908	0.018
Ye x si(re)	16	78564	4910.2	4.1875	0.001
si(re) x st	24	1.92E+05	8016.3	6.8364	0.001
Ye x re x st**	3	9304.7	3101.6	1.4742	0.129
Ye x si(re) x st**	15	31762	2117.5	1.8058	0.001
Res	1042	1.22E+06	1172.6		
Total	1140	2.82E+06			

Table 4-2. Variance estimates table based on the PERMANOVA in Table 1. Estimates of components of variation are shown as percentages.

Source	Estimate	Square root	Percent
S(year)	13.053	3.613	0.42
S(region)	362.39	19.037	11.65
S(stratum)	271.32	16.472	8.72
V(site(region))	562.11	23.709	18.07
S(yexre)	17.008	4.1241	0.55
S(yexst)	17.549	4.1892	0.56
S(rexst)	59.551	7.7169	1.91
V(yexsi(re))	168.78	12.992	5.43
V(si(re)xst)	364.81	19.1	11.73
S(yexrexst)	18.487	4.2996	0.59
V(yexsi(re)xst)	82.225	9.0678	2.64
V(Res)	1172.6	34.243	37.70

The biological communities at the sites in the KBAY and KATM regions formed fairly distinct regional groups in the nMDS for both intertidal strata, while sites from all PWS regions and KEFJ strongly overlapped (Figure 4-3). These trends were stronger in the mid than the low intertidal. In contrast, there were no clearly defined groupings of the biological communities when categorized by static attribute clusters (Figure 4-4). Sites from multiple regions shared static attribute groupings (i.e., static attribute groups were spread across regions). This demonstrates that the regions did not consistently differ in the static attributes that were measured in this study. The one-way ANOSIMs based on the biological community data confirmed the lack of significance in the static attribute groupings (mid intertidal ANOSIM $R=0.207$; low intertidal ANOSIM $R=0.177$). These results indicate that the biological communities in the northern GOA are not strongly influenced by the static attributes that were measured in this study.

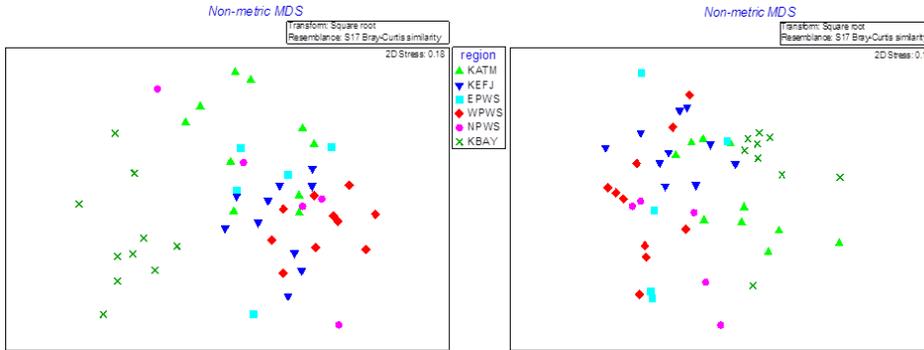


Figure 4-3. nMDS from the mid (left panel) and low (right panel) intertidal with sites color coded and grouped by region. Site distribution is based on biological communities.

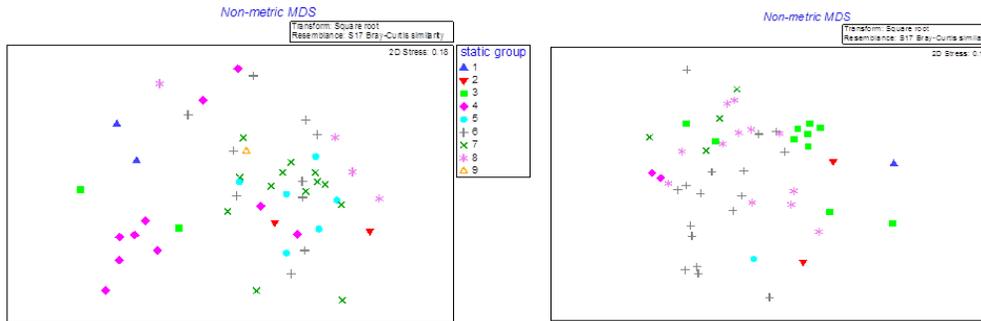


Figure 4-4. nMDS from the mid (left panel) and low (right panel) intertidal with sites color coded by static attribute cluster. Site distribution in the nMDS is based on biological communities.

Although overall, static habitat features had little influence on biological communities, the relative importance of habitat features differed between the mid and low intertidal. The mid was most influenced by fetch at 200 m, slope at 0.5, tidal glacial presence, rock, and gravel (BEST-BIOENV routine). Here, fetch and gravel were most responsible in separating sites in KBAY from those in other regions. While KATM formed a fairly distinct regional group, none of the measured attributes clearly explained this separation (Figure 4-5). In the low intertidal, fetch at 500 m, exposure, distance to freshwater, tidal glacial presence, and mud/sand were most influential (BEST-BIOENV routine). Here, mud/sand separated most sites in KATM and exposure and fetch at 500 m separated most sites in KBAY from other regions, but this separation and direction of static drivers was not strong (Figure 4-5).

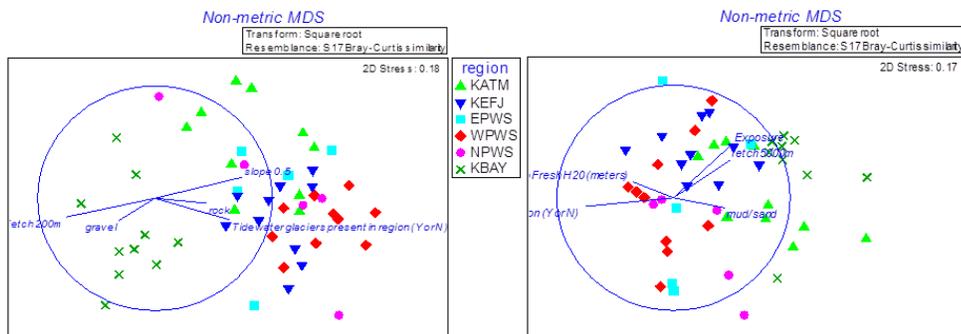


Figure 4-5. nMDS from the mid (left panel) and low (right panel) intertidal with sites color coded and grouped by static attribute. Site distribution is based on biological communities.

Overall, in the northern Gulf of Alaska, local static attributes, as defined in this analysis, explained little of the structure of biological communities. Static habitat attribute-based groupings differed from regional groupings, indicating that there were no consistent differences in static habitat attributes by region. This is not surprising because sites were not chosen to necessarily have similar physical attributes. These results indicate that there are additional regional drivers, either static or dynamic, that may be specific to each of the regions (i.e., WPWS, EPWS, NPWS, KEFJ, KATM, and KBAY). Other intertidal areas have exhibited similar results for diversity, showing greater differences among sites within a region when compared with differences between regions (deJuan and Hewitt 2010). Understanding the importance of static attributes will allow us to tease them apart as much as possible from the role of temporally more dynamic drivers in these regions, particularly in the context of long-term monitoring of these communities and climate variation. For example, as mentioned before, some of the static attributes included in this analysis, such as distance to freshwater input and the regional presence of tidewater glaciers may be static but the amount of discharge from these sources is not. The inclusion of key static variables as covariates in future analyses of trends in community structure over time should help improve our ability to detect important temporal patterns and their causes while accounting for the influence, albeit small, of habitat features. In addition, while the overall species pool for the more common and dominant species is probably relatively similar throughout the Gulf of Alaska, these data imply that some drivers are playing a role in dictating species occurrence at a local/site level, contributing to site-specific differences in biological communities. The determination of these drivers are our next step.

References

- Burrow, M.T., R. Harvey, and L. Robb. 2008. Wave exposure indices from digital coastlines and the prediction of rocky shore community structure. *Mar Ecol Prog Ser* 353:1-12.
- Cooney, R.T., J.R. Allen, M.A. Bishop, D.L. Eslinger, T. Kline, B.L. Norcross, C.P. McRoy, J. Milton, J. Olsen, V. Patrick, A.J. Paul, D. Salmon, D. Scheel, G.L. Thomas, S.L. Vaughan, and T.M. Willette. 2001. Ecosystem controls of juvenile pink salmon (*Onchorynchus gorbuscha*) and Pacific herring (*Clupea pallasii*) populations in Prince William Sound, Alaska. *Fisheries Oceanography* 10:1-13.

- deJuan, S., and J. Hewitt. 2011. Relative importance of local biotic and environmental factors versus regional factors in driving macrobenthic species richness in intertidal areas. *Marine Ecology Progress Series* 423:117-129.
- Gay, S.M., and S.L. Vaughan. 2001. Seasonal hydrography and tidal currents of bays and fjords in Prince William Sound, Alaska. *Fisheries Oceanography* 10:159-193.
- Konar, B., K. Iken, and M. Edwards. 2009. Depth-stratified community zonation patterns on Gulf of Alaska rocky shores. *Marine Ecology* 30:63-73.
- Meager J.J., T.A. Schlacher, and M. Green. 2011. Topographic complexity and landscape temperature patterns create a dynamic habitat structure on a rocky intertidal shore. *Marine Ecology Progress Series* 428:1-12.
- P.R. Mundy. 2005. *The Gulf of Alaska: biology and oceanography*. Alaska Sea Grant College Program.
- Schoch, G.C., and H. Chenelot. 2004. The Role of Estuarine Hydrodynamics in the Distribution of Kelp Forests in Kachemak Bay, Alaska. *Journal of Coastal Research* SI(45):179-194.
- Zacharias M.A. and J.C. Roff. 2001. Explanations of patterns of intertidal diversity at regional scales, *Journal of Biogeography* 28: 471–483.

PACIFIC BLUE MUSSEL (*MYTILUS TROSSULUS*) ABUNDANCE IN THE GULF OF ALASKA: SYNTHESIS OF GULF WATCH DATA (2006-2013) AND A CONSIDERATION OF MAJOR RECRUITMENT EVENTS (1989-2013)

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Introduction

Pacific blue mussels (*Mytilus trossulus*) are abundant and wide-spread primary consumers in the intertidal zone throughout the Gulf of Alaska (GOA). As a component of the Gulf Watch Alaska monitoring program, they represent a key member of intertidal communities and an important prey resource to a number of nearshore vertebrate predators. Our goal is to understand variation in abundance of *M. trossulus* over large temporal and spatial scales and over a variety of habitats in the northern GOA to determine the bottom-up factors that influence recruitment and the top-down forces that control total biomass. This information is needed to predict consequences of variation due to incremental climate change, periodic regime shifts, and catastrophic change caused by oil spills or natural events such as severe winters.

M. trossulus occurs along sheltered shorelines on both rocky and cobble dominated substrates, where they, along with a variety of barnacles, the brown alga *Fucus distichus*, and other benthic marine algae, are the primary occupiers of space (Nybakken 1969, Feder & Keiser 1980, O'Clair & Zimmerman 1986, Klinger & Fukuyama 2011). In the absence of predation or disturbance, *M. trossulus* can out-compete other intertidal invertebrates and algae to become the dominant space occupiers, forming near monotypic stands within the middle intertidal zone (O'Clair & Zimmerman 1986). However, monotypic stands of mussels rarely occur due to removal by an array of nearshore predators, including sea stars, predatory snails, sea otters, black oystercatchers, Barrow's goldeneye, and harlequin ducks (Paine 1974, Trust et al. 2000, Dean et al. 2002, Esler et al. 2002, Hipfner & Elner 2013), and by physical disturbance, e.g., strong wave action, ice scour, and stress due to extreme warm or cold temperatures (Hunt & Scheibling 1996, 1998, Gutt 2001). Mussels are key components of intertidal communities in the northern GOA, both because of their potential dominance in the system and because they provide critical food resources to a variety of nearshore predators. In addition, mussels are a foundation species, having the potential to dramatically affect communities and ecosystems, as they can alter habitats through construction of dense beds, and can link benthic and pelagic systems through filtration of the water column and deposition in the benthos (Suchanek 1986, Seed & Suchanek 1992).

1. Analyze Gulf Watch Data, 2006-2013.
 - a. Determine if observed changes in mussel abundance varied independently or synchronously among regions of the GOA over the period of this study (2006-2013), by examining broad-scale patterns in inter-annual and spatial variation in mussel abundance across three areas in the northern GOA spread over >500 linear km.
 - b. Determine if diets of two key nearshore vertebrate predators of mussels (sea otters [*Enhydra lutris*] and black oystercatchers [*Haematopus bachmani*]) respond to changes in mussel abundance/total caloric pool by correlating changes in mussel abundance with changes in proportion and sizes of mussels in their diets within each region.
2. Examine all available mussel data to evaluate the frequency of large-scale recruitment events
 - a. Determine longer temporal patterns in large-scale recruitment events in the GOA by examining mussel data sets dating back to 1989, and
 - b. Compare observed temporal changes in mussel abundance patterns identified over the last 25 years with a variety of indicators of oceanic conditions that may represent potential environmental drivers of mussel recruitment events.

This synthesis focuses on *M. trossulus* in the GOA where the dynamics of this important nearshore prey species are very different from the more often studied *M. californianus* in the California Current system. To date, most studies of Pacific mussels have examined a similar species, *M. californianus*, which inhabits high-energy open coasts, generally located within upwelling systems (Connolly et al. 2001, Garza 2005, Blanchette & Gaines 2007, Menge et al. 2009, Smith et al. 2009, Wootton & Forester 2013). In these systems, mussel recruitment is generally not limiting and most studies have focused on local removal effects (e.g., disturbance and predation by invertebrate predators), which were found to be important regulators of adult mussel population dynamics over relatively small geographic scales (i.e., 10's of km) and short temporal scales (e.g., < 10 yrs).

In contrast to areas where most mussel studies have been conducted, the GOA is characterized by downwelling conditions (Mundy 2005), and thus intertidal invertebrate recruitment patterns in the GOA likely differ from those in upwelling systems. Also, *M. trossulus* occurs on more protected coasts than *M. californianus* and is an important prey species for a larger number and variety of nearshore vertebrate predators that occur in these protected waters, including concentrations of wintering sea ducks (Vermeer 1983, Goudie & Ankney 1986, Robertson & Goudie 1999, Anderson & Lovvorn 2012, Waldeck & Larsson 2013), summer nesting black oystercatchers (Webster 1941, Hartwick 1976, Meire & Ervynck 1986, Cayford & Goss-Custard 1990) and year-round resident sea otters (VanBlaricom 1988, Doroff & DeGange 1994). The relative importance of regulating factors for *M. trossulus* in the GOA are likely different from those described for *M. californianus* along open coasts in upwelling systems. The Gulf Watch Alaska program provides monitoring data from within the portion of the GOA that lies between eastern Prince William Sound and the southwest end of Katmai National Park on the Alaska Peninsula (Figure 4-6) that allows examination of factors influencing intertidal communities within a downwelling system, in contrast with paradigms derived from other nearshore systems.

Factors controlling mussel abundance.

While mussel abundance and distribution are generally thought to be controlled by competition for space, predation, or physical disturbance (based on studies of *M. californianus*), larval supply presumably also could be important. Mussels, like many marine invertebrates, have a planktonic stage as part of their life history, and their persistence depends on successful settlement of their drifting propagules and survival of newly settled recruits. Studies of *M. trossulus* in Prince William Sound showed they develop gametes over the winter and spawn from March to August, with peaks generally occurring in May and June (Feder & Keiser 1980, Blanchard & Feder 1997). Initiation of spawning correlated with increasing temperature and decreasing salinity. *M. trossulus* veligers have a pelagic larval duration of three to seven weeks (O'Clair & O'Clair 1998), and during peak spawning periods, mussel veligers can be the numerically dominant meroplankton, potentially dispersing over hundreds of kilometers before settlement, given the right conditions (Bayne 1976, Levinton & Koehn 1976). Little is known about influences on *M. trossulus* larvae survival in wild populations; however, survival rates are presumed to be low and, for *M. edulis* (a species occurring on the Atlantic coast), it is estimated that less than one percent survive the free swimming stage (Bayne 1976). Growth and survival of planktonic larvae are influenced by availability of food resources and temperature fluctuations, but predation is thought to be the primary cause of mortality (Bayne 1976, Widdows 1991, Phillips 2004, Yaroslavtseva & Sergeeva 2006).

Environmental conditions that favor successful mussel settlement and recruitment into adult populations are not well understood, but probably relate to periods when growth and survival of pelagic larvae are enhanced (Widdows 1991, Phillips 2004). Growth and survival of larval stages are related. Faster growth leads to faster time to settlement and reduces the time larvae are in the water column, where they are especially susceptible to predation and other sources of mortality. Generally, strong recruitment correlates with high pelagic primary production, although larval retention near shore is also important.

“Supply-side” ecology (Gaines & Roughgarden 1985, Lewin 1986, Roughgarden et al. 1988, Grosberg & Levitan 1992, Underwood & Keough 2001, Lee & Bruno 2009) demonstrates that variable propagule supply and recruitment success can be important factors influencing population structure and dynamics of adult intertidal organisms, with cascading effects to upper trophic levels (Witman et al. 2003). Further, the supply and success of propagules may be coupled to large-scale variations in oceanic conditions (Menge 2000, Menge et al. 2003, Schiel 2004, Navarrete et al. 2005, Broitman et al. 2008, Menge et al. 2009). The implication of benthic-pelagic coupling includes the expectation that climate-driven changes in oceanic conditions may affect nearshore communities due to changes in invertebrate recruitment success (Menge et al. 2009).

As part of Gulf Watch Alaska, *M. trossulus* populations are monitored over a relatively large spatial scale (>500 km spread across all sites) and a long temporal scale (i.e., potentially >20 years into the future). We are concurrently examining utilization of *M. trossulus* by two higher trophic level vertebrate predators: sea otters and black oystercatchers. Thus, we are positioned to understand sources of variation in nearshore ecosystems of the GOA. We have the unprecedented opportunity to: 1) examine the scale at which *M. trossulus* recruitment patterns and adult population dynamics are synchronized and consider the influence of large-scale oceanic and climatic variation; 2) examine how higher trophic level vertebrate predators influence abundance of *M. trossulus* over a broad geographic area; and 3) study how changes in *M. trossulus* standing stock (through variation in recruitment and removal due to predation and physical processes) may influence a variety of performance metrics for nearshore vertebrate predators (e.g.,

foraging efficiency, caloric intake rate, reproductive success, survival, and ultimately population dynamics).

In this report, we present information collected thus far, which suggests that *M. trossulus* is recruitment-limited in the GOA. Further, our data suggest that strong recruitment events that increase mussel standing stocks occur intermittently across large spatial scales, mussel abundance is annually variable due to variation in both recruitment and removal processes, and variation in the mussel utilization patterns of nearshore vertebrate predators is related to mussel abundance (especially for predators specializing on mussels or for all invertebrate predators within locations with limited alternative invertebrate prey).

This preliminary assessment of broad scale patterns will help guide future investigations. A final analysis will require a longer time-series of the broad-scale, directly-comparable data being collected as part of Gulf Watch Alaska, as well as analyses that incorporate local scale physical factors and site-specific variability. However, the information presented here provides an example of the kinds of large-scale questions that can be addressed using Gulf Watch data.

Study Area

We examined the temporal and spatial patterns of mussel abundance and size distributions at 5 randomly selected sites in sheltered rocky habitats within each of three regions: Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ) and Western Prince William Sound (WPWS, Figure 4-6). These regions span >500 km of the northern GOA and include a diverse geography. KATM lies on the Alaska Peninsula and is characterized by broad shallow bays, with large tidal influences from Cook Inlet and Shelikof Strait that contribute to making the coastal waters highly productive. KEFJ is located on the Kenai Peninsula and contains both open outer coast headlands and deep fjords whose watersheds are predominately glacier fed. Shallow habitats within KEFJ are generally limited to the narrow band along the steep shoreline and glacial moraines near the back of most fjords. Prince William Sound is a semi-enclosed sea with abundant fresh water inputs. Hinchinbrook, Hawkins, and Montague Islands are the principal islands that protect the Sound from the GOA. Prince William Sound includes a complex coastline with many islands within its interior and glacial-cut fjords along its northern and western boundary. Production in WPWS is driven by a portion of the Alaska Coastal Current siphoned off the GOA through Hinchinbrook Entrance and circulating back out through the passages of WPWS (Montague Strait; Latouche, Elrington, Prince of Wales, and Bainbridge Passages). We used generalized random tessellation stratified (GRTS) sampling (McDonald 2004, Stevens Jr & Olsen 2004) to select five rocky sites per region that provided a random yet spatially balanced distribution of sites within each of these three regions.

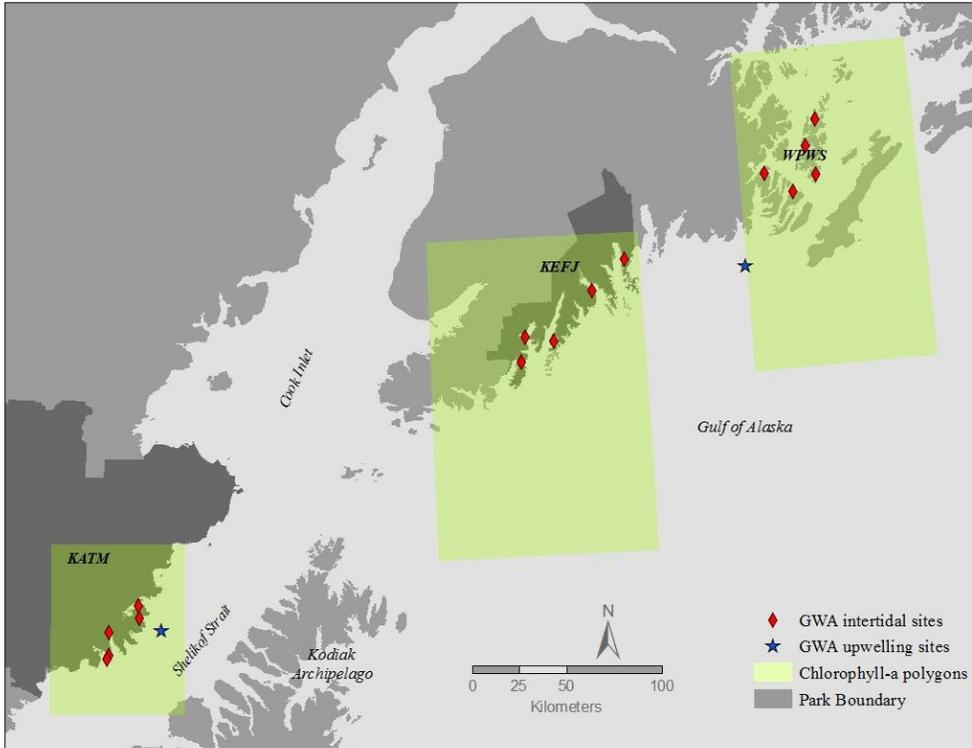


Figure 4-6. Intertidal sampling sites within Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Western Prince William Sound (WPWS). Rocky intertidal sampling sites were selected using a GRTS sampling scheme. The nearest continuous mussel bed to each randomly selected rocky intertidal site became the “selected” mussel sampling site. Blue stars represent the location of predicted upwelling conditions and green polygons represent spatial coverage of satellite-derived chlorophyll-a concentrations.
[HTTP://WWW.PFEG.NOAA.GOV/PRODUCTS/PFEL/MODELED/INDICES/NOIX/NOIX.HTML](http://www.pfeg.noaa.gov/products/pfel/modeled/indices/noix/noix.html)

Methods

Objective 1: Analyze Gulf Watch data

Percent cover of mussels at randomly selected sheltered rocky sites.

We measured percent cover of mussels (and other sessile invertebrates and algae), as well as density of predatory whelks (*Nucella* spp. and *Lirabuccinum dirum*) and several sea star species, at each site. Sampling followed Gulf Watch Alaska protocols (<http://portal.aos.org/gulf-of-alaska.php#metadata/53c052b6-8874-46d1-b40a-acc615a3879a/project>). We conducted sampling during spring tides in June and July. Sampling at KATM began in 2006 and was done annually thereafter through 2013 except for 2011. At KEFJ, annual sampling was done from 2008-2013, while sampling in WPWS occurred in 2007 and then from 2010-2013.

At each site, we estimated percent cover of mussels within each of twelve 0.25 m² quadrats placed 1.5 m above mean lower low water (MLLW) along a 50 m-long transect. The twelve quadrats were

systematically positioned along transects based on a random start point uniquely selected each year. Within quadrats, we determined presence or absence of mussels at a total of 49 (in 2006 and 2007) or 25 (2008 on) systematically placed points, and percent cover was calculated based on the proportion of points occupied by mussels.

Mussel bed size, mussel density, and mean size of mussels at selected mussel bed sites.

In addition to the rocky intertidal sites, we sampled mussel beds in close proximity to the rocky sites. Mussel beds were initially identified as areas with mussels that were contiguous (< 1 m gap between mussels) over a >50-m long section of shoreline, and as close as possible to the randomly selected rocky sites (generally within 1 km or less, Figure 4-6). We began sampling in 2008 at both KATM and KEFJ and in 2010 at WPWS, and annually thereafter except at KATM where there was no sampling in 2011.

Within each of 15 selected mussel beds (5 beds per region), we estimated the area of each bed, the density of mussels ≥ 20 mm in length, the size distribution of mussels ≥ 20 mm in length, and the density of all mussels ≥ 2 mm. We focused on larger (≥ 20 mm) mussels because black oystercatchers and sea otters generally consume mussels of larger size (Webster 1941, Hartwick 1976, VanBlaricom 1988, Cayford & Goss-Custard 1990, Andres 1999, Dean et al. 2002). We estimated mussel bed size, density, and size distribution as follows. At each site, we established a fixed horizontal 50-m transect near the upper elevation of the mussel distribution. We then established ten systematically placed vertical transects along the horizontal transect using a random start point. Different vertical transect positions were determined each year based on a new random start point. Vertical transects extended from the top of the mussel bed (i.e., could extend above the horizontal transect) to MLLW. Along each vertical transect, we estimated the upper and lower boundaries of the bed by noting the presence or absence of mussels under the vertical transect tape (i.e., ~15 mm width). Lower mussel bed boundaries were defined by the last mussel under the tape or by a gap of > 1 m in which no mussels were found.

We estimated size of each bed as the sum of the areas represented by each vertical transect (i.e., the sum of the 10 vertical bed measurement lengths multiplied by 5 m). We estimated mussel density and size distributions from single quadrats placed along each of the ten vertical transects (ten total quadrats per site). The position of each quadrat was randomly selected as a proportional distance from the upper to the lower boundary of the mussel band for each vertical transect. The density of larger (≥ 20 mm) mussels was estimated in quadrats ranging in size between 0.004 and 1 m², which we adjusted to accommodate for the wide range in mussel densities observed. That is, we adjusted quadrat size such that we could obtain ~20 mussels per quadrat of ≥ 20 mm in size as opposed to sampling hundreds of mussels at high densities or sampling few if any mussels at low densities using a single, set quadrat size. Once a quadrat size was determined, all mussels ≥ 20 mm within each quadrat were counted to determine density (expressed as number·m⁻²) and measured to the nearest mm for determination of size distribution. In addition, we collected and counted all mussels ≥ 2 mm from within smaller (0.00203 m²) PVC core samplers placed just outside the upper left margin of each quadrat used for sampling larger mussels. These smaller cores were designed to provide an estimate of the density of mussels of all size classes, including newly recruited mussels, and to identify mussel recruitment events. However, primary settlement often occurs very low in the intertidal or in the subtidal on algae (Seed 1976), thus our cores reflect mussel recruitment levels after secondary settlement has occurred.

We estimated the total number of ≥ 20 mm mussels within each mussel bed as the product of bed size and the density of mussels within each bed. We then estimated total mussel energy content (joules) available within each mussel bed for each sampling period by first converting mussel size distributions to dry mass;

$$\text{Dry mass} = 0.000011 \times \text{length}^{(2.843)} \quad (1)$$

and then from dry mass to energy content by multiplying by 17.33 J mg^{-1} using the conversions for *M. trossulus* given in Dean et al. (2002). We then computed the mean energy content available for the average mussel within each bed, and then multiplied this by the total number of ≥ 20 mm mussels.

Mussels in the diets of black oystercatchers and sea otters.

We estimated the proportion and sizes of mussels in diets of two nearshore vertebrate predators, black oystercatchers and sea otters. Sampling at KATM began in 2006 and was repeated annually through 2013, except in 2011. At KEFJ, annual sampling began in 2007, while sampling in WPWS was conducted in 2007 and then annually starting in 2010.

For black oystercatchers, we examined the proportion and size of mussels in prey provisioned to chicks at nest sites. Within each region, we conducted boat-based surveys at five, 20 km coastal transects centered on the GRTS selected rocky intertidal algal and invertebrate sampling sites (Figure 4-6). We identified potential active black oystercatcher nest sites by presence of one or more adults, and each accessible site was visited to determine the presence or absence of nests and the number of chicks and/or eggs present. We collected, counted and measured all fresh prey remains (e.g., mussel, limpet, chiton, and whelk shells) present at a nest site and identified prey items to species and measured them to the nearest mm. Because the number of nests on transects was relatively small, we supplemented black oystercatcher diet information with prey collections from off-transect nests located opportunistically during the course of other fieldwork in the vicinity of the intertidal sites.

We estimated sea otter prey composition and prey size via shore-based or vessel-based observations of randomly selected foraging otters. Shore-based observations limited data collection to sea otters feeding within approximately 1 km of shore, although most observations occur within ≤ 500 m of the observer. High powered telescopes (Questar Corp., New Hope, PA.) and 10X binoculars were used to observe prey type, number, and size class during foraging bouts of focal animals (Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.). A forage bout was defined as a group of observations of repeated dives for a focal animal while it remained in view and continued to forage (Calkins 1978, Doroff & DeGange 1994). Foraging observations were generally made within a 10 km radius of each of the five established rocky intertidal invertebrate and algal sites, although otter distribution occasionally required adjustment to the closest aggregation of observable otters. We estimated size of prey items based on comparisons with average sea otter paw size of 5 cm (USGS unpublished data) by categorizing prey as < 5 cm, 5-10 cm and > 10 cm similar to Doroff and DeGange (1994) with each major size class further subdivided into 3 equal subclasses. In this report, we will focus only on sea otter diet data from KEFJ and WPWS because we rarely observed sea otters at KATM consuming *M. trossulus* (see results).

Objective 2: Examine available mussel data to evaluate frequency of large-scale mussel recruitment events

We defined large-scale mussel recruitment events as points in time when wide-spread increases in mussel abundance occurred. These likely reflect conditions favorable for strong mussel settlement and successful recruitment at the GOA wide-scale. We recognize the importance of site specific variability in mussel recruitment and the occurrence of some level of annual recruitment at most sites; however, our focus was on broad-scale recruitment events. Recognizing that Gulf Watch Alaska program sampling captured both the rise and fall in mussel abundance only at KATM, our measurements of percent cover of mussels (see results) suggest abundance may have peaked within all regions in 2008. This finding, along with our observations of wide-spread mussel settlement in 2007, suggests we observed one large-scale *M. trossulus* recruitment event between 2007 and 2013 (see results). Thus, we examined additional historical data sets that included measurement of mussel abundance in the GOA for evidence of other large-scale recruitment events over the 25-year period from 1989 through 2013 (Table 4-3). These data sets originated from sites in WPWS and Kachemak Bay, and include both published (Highsmith et al. 1994, Houghton et al. 1997, Coats et al. 1999, Lindeberg et al. 1999, Mearns et al. 2012, Shigenaka 2014) and unpublished data sets. With the exception of estimates derived from photographs at locations in Prince William Sound (Mearns et al. 2012), none of the records from other studies have been continuous over this period.

Table 4-3. Studies of mussel abundance in the GOA, 1989 to 2013.

Reference	Study area	Metric examined	Number of sites examined	Years covered
Mearns et al. (2012)	PWS	Percent cover	3	1989-2013
Highsmith et al. (1994)	PWS	Percent cover	10	1990-1995
Lindeberg and Saupe (unpublished)				
Houghton et al. (1997)	PWS	Percent cover	5 to 8, depending on year	1989-1997
Coats et al. (1999)	PWS	Density	11	1989-1997
Lindeberg et al. (1999)	PWS	Density and size	4	1993-1997
Shigenaka (2014)	Kachemak Bay		1	1999-2013
Konar and Iken, unpublished	Kachemak Bay	Percent cover	5 – 3 depending on year	2005-2013
This Study	KATM	Percent cover	5	2006-2013
This study	KEFJ	Percent cover	5	2008-2013
This study	PWS	Percent cover	5	2007-2013

Preliminary examination of possible environmental drivers of large-scale recruitment events

We examined graphs to detect obvious relationships between hypothesized synchronous broad-scale recruitment events and a variety of indices of oceanic conditions including: 1) monthly upwelling/downwelling strength, 2) monthly pelagic productivity as measured by chlorophyll-a concentrations, 3) monthly freshwater discharge, 4) monthly average sea water temperature and salinity

profiles, and monthly or bimonthly indices of large-scale conditions including; 5) Pacific Decadal Oscillation (PDO), 6) El Niño/Southern Oscillation (ENSO), 7) North Pacific Gyre Oscillation (NPGO) and 8) Northern Oscillation Index (NOI). Based on similar graphical analysis, Shigenaka (2014) hypothesized PDO conditions may influence mussel densities in Kachemak Bay, and Mantua et al. (1997) described PDO effects on salmon production in the North Pacific. More rigorous quantification of these relationships would require a more robust data set, such as the one we are generating through Gulf Watch; the intent of this exercise was to look for obvious patterns that might warrant additional investigation.

Sources for the various oceanographic data sets are listed in Table 4-4. For some of these, we defined the spatial extent of the data of interest. Specifically, we obtained predictions of upwelling strength at two locations (Figure 4-6); one just off the KATM coast (Longitude 154W, Latitude 58.2N) and another at a location between KEFJ and WPWS (Longitude 148.5W, Latitude 59.8N). We looked for productivity anomalies as measured by chlorophyll-a concentrations at our three regions (Figure 4-6); KATM (58.6N-57.8N, 155W-153.8W), KEFJ (60N-58.5N, 151.5W-149.5W), and WPWS (60.8N-59.3N, 148.5W-146.8W) using SeaWiF S 9km for data for the period 1 Sept, 1997 to 1 July, 2002 and MODIS-Aqua 4km data thereafter.

Table 4-4. Sources of data for indices of oceanic conditions in the GOA between 1989 and 2013.

Index	Source
Upwelling	http://www.pfeg.noaa.gov/products/las/docs/global_upwell.html
Chlorophyll-a	http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month
Freshwater	http://www.ims.uaf.edu/gak1/Discharge.dat
Water temp. and salinity	http://www.ims.uaf.edu/gak1/GAK1_CONTOUR_ANOMALIES.png http://www.ims.uaf.edu/gak1/GAK1_CONTOUR_ANOMALIES.png
PDO	http://jisao.washington.edu/pdo/PDO.latest http://jisao.washington.edu/pdo/PDO.latest
ENSO	http://www.esrl.noaa.gov/psd/enso/mei/table.html
NPGO	http://www.o3d.org/nngo/nngo.php http://www.o3d.org/nngo/nngo.php
NOI	http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOI/noix.html

We do not have data on specific timing of mussel spawning and settlement, thus we represented good recruitment years graphically as spanning an entire year beginning in 1 May and assuming peak spawning occurs 1 June (Feder & Keiser 1980, Blanchard & Feder 1997).

Results

Objective 1: Analyze Gulf Watch data

Percent cover of mussels at randomly selected sheltered rocky sites

In 2007, we noted a large number of newly recruited mussels (estimated length of <10 mm) at many of the rocky intertidal sampling sites in each of the three regions (KATM, KEFJ, and WPWS; personal observations by T.A. Dean, J.L. Bodkin and H.A. Coletti). At KATM, where sampling was initiated in 2006, the recruitment of mussels in 2007 was reflected in the sharp increase in percent cover of mussels

from the previous year (Figure 4-7), which resulted in peak percent cover measurements in 2008. At KEFJ, the maximum percent cover measurement also occurred in 2008, and declined thereafter consistent with the pattern observed at KATM (Figure 4-7). In WPWS, our highest percent cover was observed in 2007, however, we did not sample there in 2008 or 2009 (Figure 4-7). Over-all, mussel percent cover was higher at KEFJ than in either KATM or WPWS, but in all regions there was a sharp decline in mussel percent cover from their peaks in 2007/2008 through 2010. Mussel percent cover remained low in all regions from 2010 through 2013. From peaks in 2007 or 2008 through 2013, declines within each of the three regions ranged from 77% to 88%. No other wide-spread recruitment events of mussels capable of substantially increasing regional-scale percent cover measurements at our rocky sites were observed between 2008 and 2013, although we did note site-specific annual recruitment that tended to be relatively consistent within sites but varied by site (personal observations by T.A. Dean, J.L. Bodkin and H.A. Coletti and mussel bed data presented below).

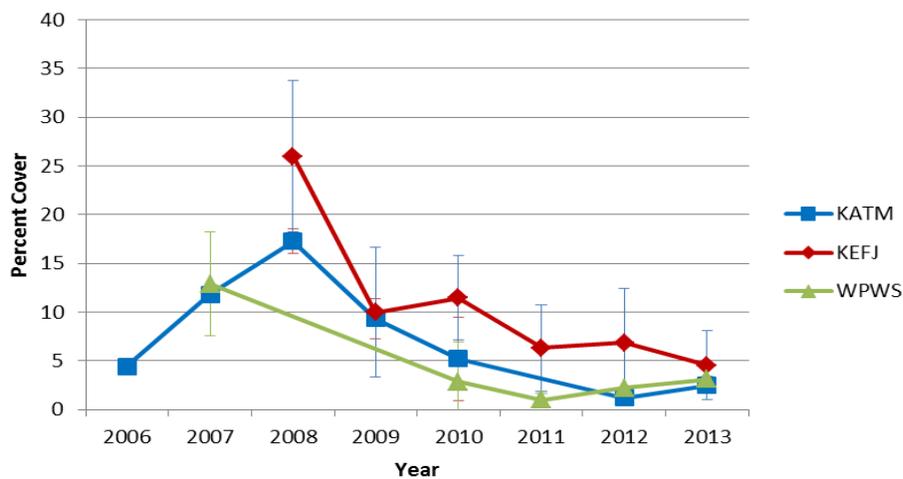


Figure 4-7. Mean percent cover of mussels at 1.5 m MLLW at rocky intertidal sites. Means and 95% confidence intervals calculated from 5 sites within each region. We calculated means and confidence intervals from square root transformed data.

While the percent mussel cover declined following the 2007 recruitment event was similar at the regional scale (Figure 4-7), the site-specific rates of declines in mussel cover were highly variable both temporally and spatially. For example, of the five rocky intertidal sites that had relatively high mussel cover in the mid intertidal (i.e., greater than 25% cover at their peak), two (Whale Bay in WPWS and Nuka Bay in KEFJ) had relatively monotonic declines in abundance between peaks in 2007/2009 and 2012, two other sites (Kafliia in KATM and Harris in KEFJ) showed sharp declines between 2008 and 2009 and relatively stable patterns of abundance thereafter, while one site (Kukak in KATM) had a slight increase in percent cover from 2008 through 2010 and a sharp decline in 2012 (Figure 4-8). These asynchronous changes likely reflect site-specific variation in the mechanisms that deplete mussel stocks, which include predation by a variety of predators, physical disturbance (e.g., ice scour) and other environmental stressors (e.g., heat stress or freezing events).

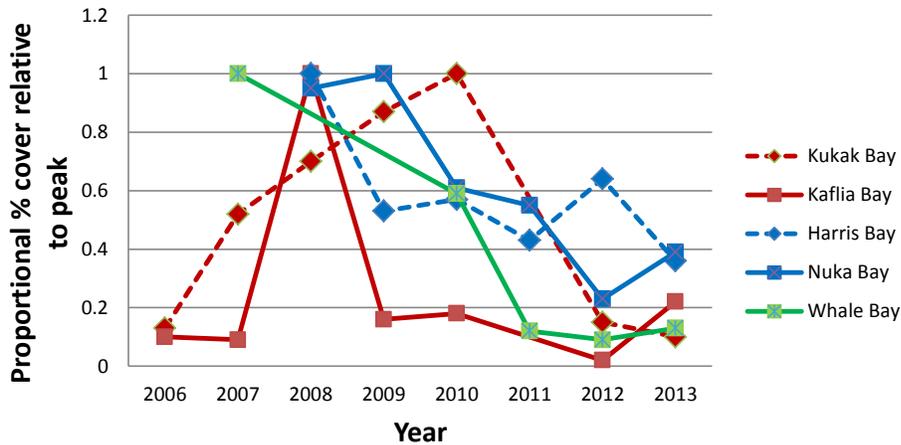


Figure 4-8. Percent cover of *M. trossulus* at 1.5 m MLLW at rocky intertidal sites where maximum percent cover peaked at greater than 25%. All percent cover values were normalized and expressed as proportion relative to peak observed mussel cover. Kukak and Kaflia Bays are located within KATM, Harris and Nuka Bays are located within KEFJ, and Whale Bay is located within WPWS

Mussel bed size, mussel density, and mean size of mussels at selected mussel bed sites

The area (m²) of monitored mussel beds was ~2X larger at KEFJ than at KATM or WPWS, but the total area of monitored mussel beds declined in all three regions over time (Figure 4-9). At KATM, monitored bed sizes declined by 69% from 2008 to 2012 then increased by approximately 50% in 2013 suggestive of regional recruitment (see KATM core data below). At KEFJ, mussel bed size decreased by 53% from 2008 through 2013 while at WPWS, mean monitored mussel bed size declined by 25% from 2010 to 2013 though we may have missed peak mussel abundance because of the later establishment of mussel sampling in this region.

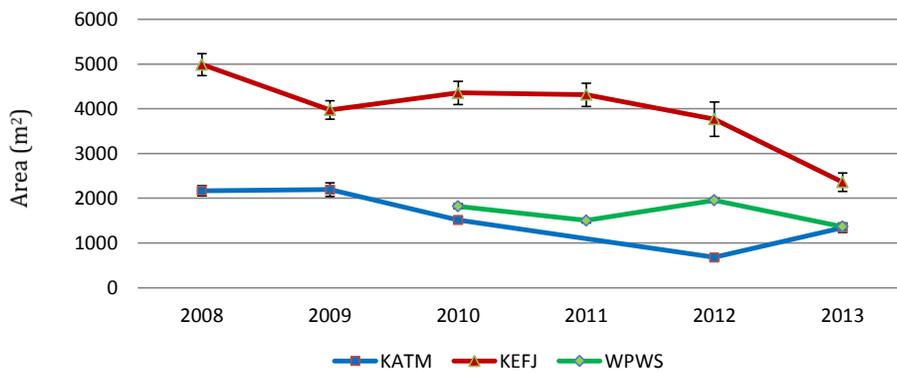


Figure 4-9. Total area (m²) of 5 selected mussel beds at each region (KATM, KEFJ and WPWS) 2008-2013. KATM was not sampled in 2011, line drawn to interpolate. WPWS was first sampled in 2010. Error bars are +/- 1 stdev.

Similar to bed size, density of large mussels (≥ 20 mm in length) was more than 2X higher at KEFJ than at KATM or WPWS, and declined over time in all three regions (Figure 4-10). At KATM, large mussel density increased slightly from 2008 to 2009 to a peak of $1,500 \text{ m}^{-2}$, but declined by 95% between 2009 and 2013 when densities reached approximately 75 m^{-2} . At KEFJ, density of large mussels declined by 50% between 2008 and 2013, from a high of $\sim 3,750 \text{ m}^{-2}$ to a low of $\sim 1,900 \text{ m}^{-2}$ although most of the decline occurred by 2010. At WPWS, large mussel densities averaged 720 m^{-2} when established in 2010 and were similar to those at KATM in that year, then declined by 81% to a low of approximately 140 m^{-2} mirroring the decline at KATM.

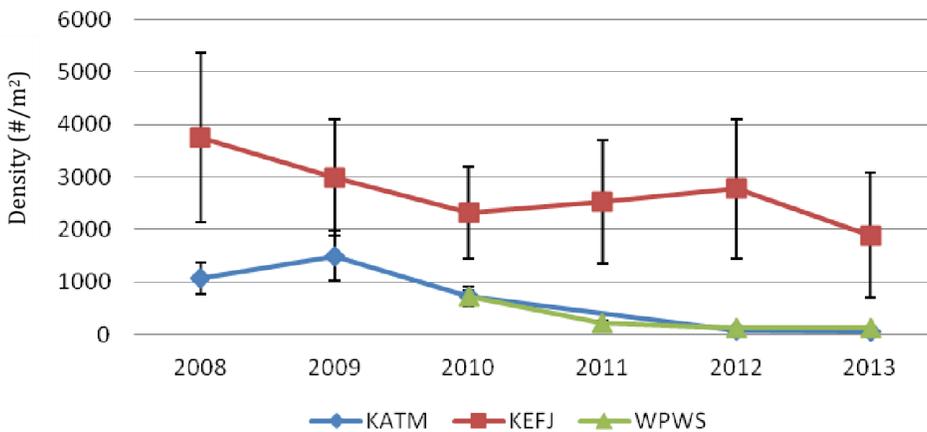


Figure 4-10. Mean density (number/m²) of large mussel (> 20 mm) from 2008 to 2013 at KATM, KEFJ, and WPWS. Error bars are +/- 1 stdev.

The mean size of large mussels (≥ 20 mm) increased between 2008 and 2010 at both KATM and KEFJ and declined in all regions between 2010 and 2013 (Figure 4-11). For all areas combined, the average mussel size decreased by 3 mm, from 27.9 mm in 2010 to 24.6 mm in 2013. In all regions, there was a notable decline in larger size classes of mussels (≥ 30 mm) between 2010 and 2013 (Figure. 4-11), which likely drove the decline in mean size.

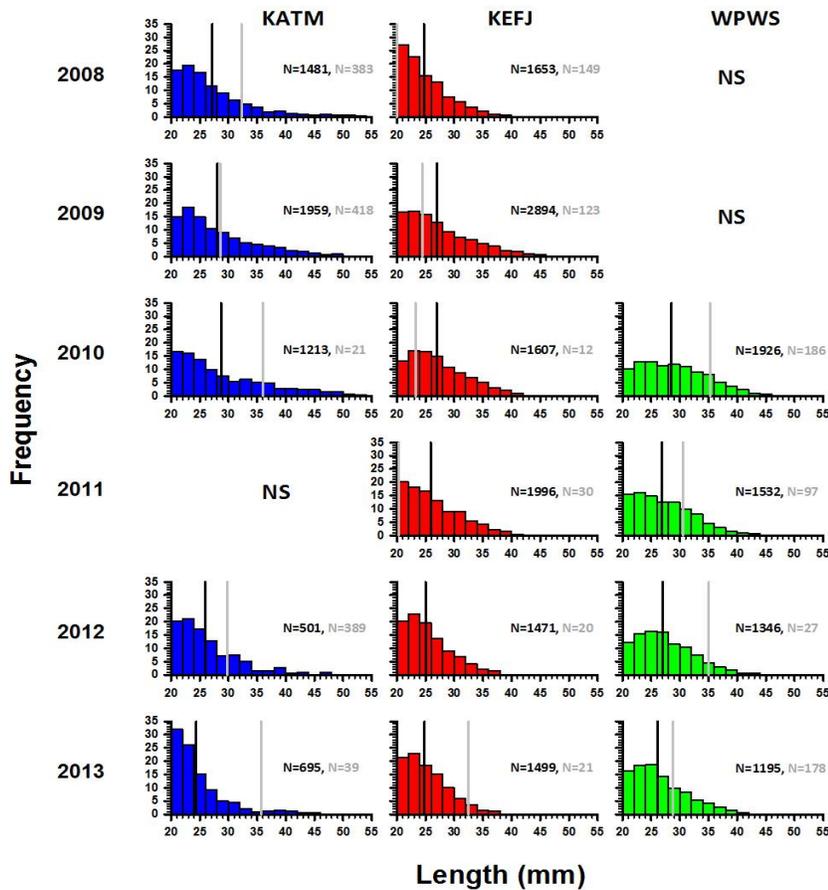


Figure 4-11. Size frequency distribution of large mussels (> 20mm) at KATM 2008-2013, KEFJ 2008-2013, and WPWS 2010-2013. Years when no sample occurred denoted by “NS”. Black lines denote mean size of mussels in mussel beds with N’s in black lettering. Gray lines denote mean size of mussels provisioned to oystercatcher chicks with sample size (N) in gray.

The estimated mean total number of mussels ≥ 20 mm in selected mussel beds (the product of bed size and mean density) and accordingly, the average energy pool available from large mussels (the product of the total number of mussels times the estimated energy content based on mussel sizes, Figure 4-12), also declined over time. Declines in energy available from mussels were much steeper than any of the other single measures of mussel abundance because of the multiplicative effects of its calculation. Through 2013, energy available from large mussels declined by 72% and 98% from their respective peaks at KEFJ (2008) and KATM (2009). Similarly, in WPWS the energy available from large mussels declined by an estimated 91% between 2010 and 2013 even though other single metrics of mussel abundance showed declines that were more modest.

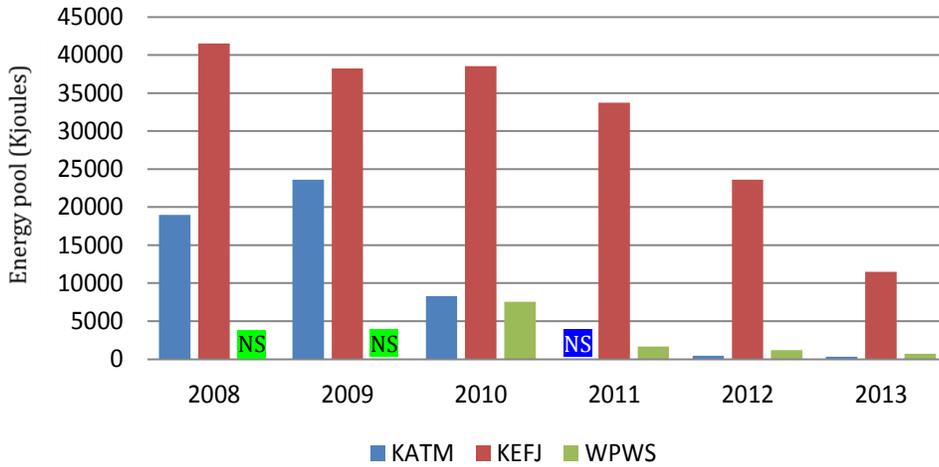


Figure 4-12. Estimated total energy pool (Kjoules) available from large mussels ($\geq 20\text{mm}$) in selected mussel beds from 2008 to 2013 at KATM, KEFJ, and WPWS calculated as total number \times mean energy content of large mussels. Total number of large mussels calculated as mean density \times mean bed size of large mussels in selected mussel beds. Bars with “NS” signify no sampling was conducted in that year.

Density of all mussels $\geq 2\text{ mm}$, as estimated from 20.3 cm^2 PVC core samples, was higher at KEFJ than either KATM or WPWS (Figure 4-13). There were no apparent trends in total mussel density over time in any of the regions. These data suggest that annual mussel recruitment was low and relatively consistent within regions between 2008 and 2013 (although variable by site), and that there were no large-scale recruitment pulses between 2008 and 2013. Unfortunately, we do not have total mussel density data from 2007, the year we observed a large-scale recruitment pulse.

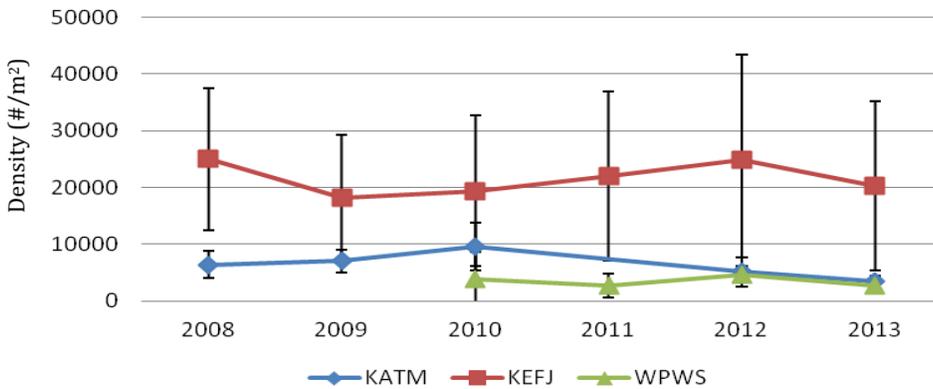


Figure 4-13. Mean density (number/m²) of all mussels ($> 2\text{mm}$) from PVC core samples from 2008 to 2013 at KATM, KEFJ and WPWS. Trends are not significant at any region. Error bars are ± 1 stdev.

Mussels in the diets of black oystercatchers and sea otters

We observed a reduction in the proportion of mussels in diets of two key nearshore vertebrate mussel predators. The mean proportion of mussels in prey that black oystercatchers provisioned to their chicks (averaged for all sites in KATM, KEFJ, and WPWS) declined from 36% in 2008 to approximately 11% in 2013. However, much of this trend was driven by a decline at KEFJ, where the proportion of mussels in the diet of oystercatchers peaked in 2008 while proportions at KATM and WPWS appeared to fluctuate without a clear trend (Figure 4-14).

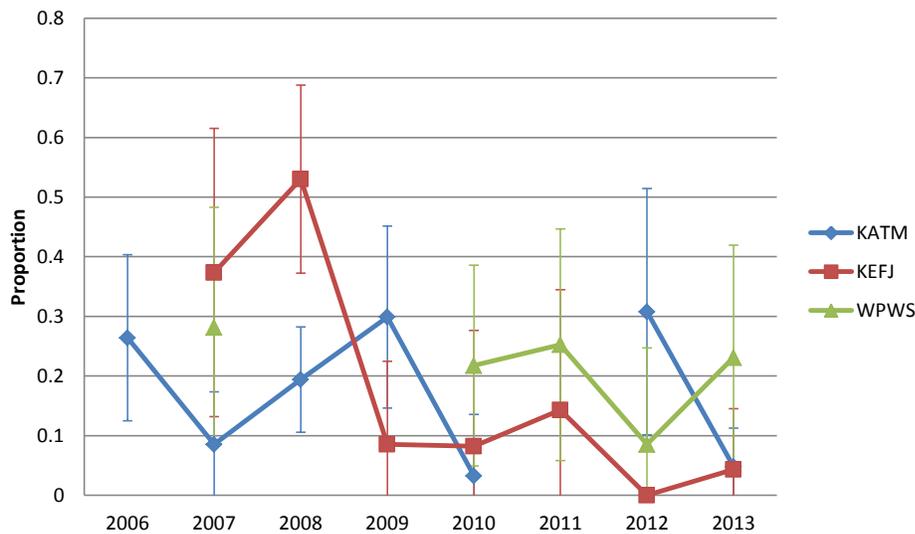


Figure 4-14. Proportion of *M. trossulus* found in black oystercatcher nests 2006-2013. Error bars indicate +/-1 stdev. Number of nests examined presented in table 4-4.

For sea otters, the most dramatic decline in the proportion of mussels in the diet also occurred at KEFJ (Figure 4-15), where sea otters utilize *M. trossulus* to a much greater degree than sea otters living in other regions (average percentage in the diet = 1%, 58% and 15% for KATM, KEFJ and WPWS, respectively; Table 4-5). From the 2008 peak when mussels made up 79% of the sea otter’s diet at KEFJ, the percent mussel in their diet declined to a low of 27% in 2012 (Figure 4-15). In WPWS, the highest proportion of mussels in the diet occurred in 2007 (30%) and then declined to a low of 6% in 2012 excluding 2008 when only 5 total feeding bouts were recorded (Table 4-3). In both KEFJ and WPWS, the proportion of clams in the diet increased as the proportion of mussels in the diet decreased (Figure 4-15).

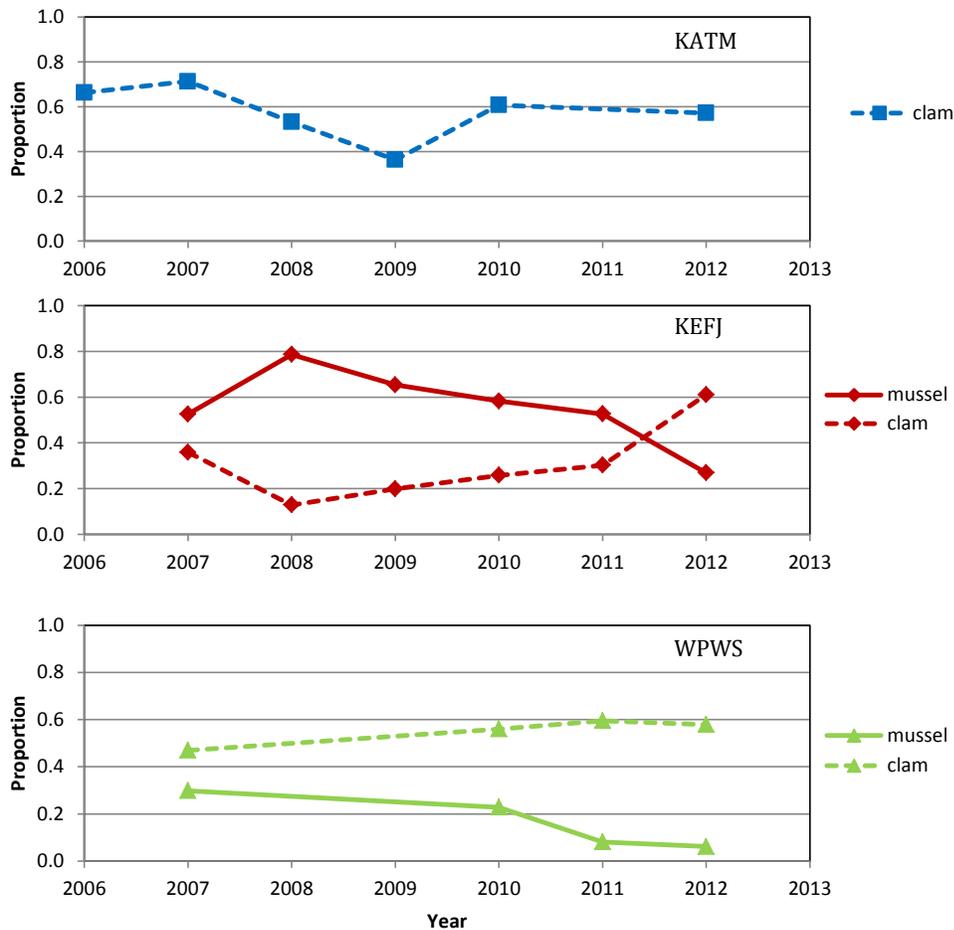


Figure 4-15. Mean proportion of *M. trossulus* and clams in the diet of sea otters at KEFJ and WPWS. Number of forage bouts presented in Table 4-3. Error bars not included for clarity. KATM (mussel) not included because sea otters rarely consumed *M. trossulus* there. Data point for WPWS 2008 not included because small sample (N = 5 bouts) did not appear representative (i.e., 96% clam).

Table 4-5. Number of sea otter forage bouts and forage dives observed by region and year. ‘.’ indicates a region not sampled in a given year. Numbers in parenthesis indicate the proportion of forage dives containing mussels from 2006 to 2012.

	KATM ¹		KEFJ		WPWS	
Year	Forage bouts	Forage dives	Forage bouts	Forage dives	Forage bouts	Forage dives
2006	65	451 (< 0.01)
2007	54	498 (0.05)	45	471 (0.53)	81	365 (0.30)
2008	38	427 (0.03)	57	392 (0.79)	5	28 (0.00)
2009	36	392 (< 0.01)	37	269 (0.65)	.	.
2010	49	522 (0.01)	57	497 (0.58)	96	581 (0.23)
2011	.	.	54	581 (0.53)	101	585 (0.08)
2012	47	436 (0.00)	33	299 (0.27)	144	813 (0.06)
Total	289	2726 (0.01)	283	2509 (0.58)	427	2372 (0.15)
¹ <i>M. trossulus</i> only identified in 53 (0.01 of total) sea otter forage dives at KATM. Thus, we excluded KATM from the sea otter mussel foraging analysis.						

Sizes of mussels that black oystercatchers provisioned to their chicks varied over time but with no clear trends (Figure 4-11) likely due to the size selective nature of oystercatcher foraging behavior or possibly the relatively small number of nests examined each year (mean = 10, 5 and 5 at KATM, KEFJ and WPWS, respectively; Table 4-6). Black oystercatchers living at KATM and WPWS obtained the largest mussels (mean = 32.1 mm, stdev = 8.6, and 32.3 mm stdev = 7.1 for KATM and WPWS respectively) compared to KEFJ (mean = 24.4 mm, stdev = 7.7), which is consistent with the size distribution of large mussels available in selected mussel beds (Figure 4-11). In addition, black oystercatchers at KATM had the most notable change in mean size of mussels provisioned to chicks when it dropped to <30 mm in 2009, although this drop was not consistent with data on the availability of large mussels in selected beds (Figure 4-11).

The mean sizes of mussels taken by sea otters at KEFJ peaked at ~27 mm in 2009 and decreased thereafter (Figure 4-16), averaging 23 mm over all years. In WPWS, mean size of mussels consumed by sea otters also averaged 23 mm with no clear trend over time (Figure 4-16).

Table 4-6. Number of Black oystercatcher nests where prey remains were collected by region and year. WPWS only had prey remains collected from on transect nests in all years sampled. ‘.’ indicates a region not sampled in a given year and ‘x’ indicates a region was surveyed but that no prey remains were observed or collected.

Year	KATM (on tx)	KATM (on+off tx)	KEFJ (on tx)	KEFJ (on+off tx)	WPWS (on tx)
2006	6	10	.	.	.
2007	5	10	4	4	5
2008	7	20	5	10	.
2009	4	9	4	4	.
2010	2	3	x	2	6
2011	.	.	2	3	5
2012	2	5	x	x	3
2013	9	11	4	4	5
Average	5	9.7	3.8	5	4.8

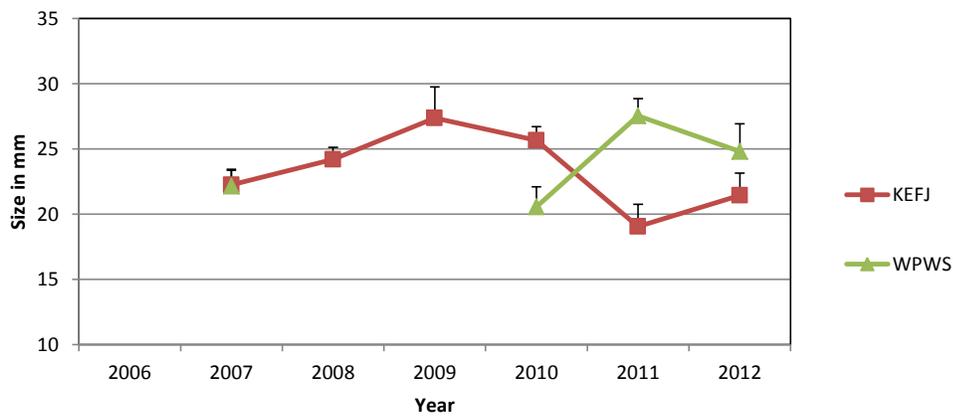


Figure 4-16. Mean size of mussels in the diet of sea otters at KEFJ and WPWS. Error bars represent ± 1 stderr. KATM not included because sea otters rarely consumed *M. trossulus* there.

Objective 2: Examine available mussel data to evaluate frequency of large-scale mussel recruitment events, 1989-2013

We obtained six additional data sets on *M. trossulus* abundance in the GOA including four from Prince William Sound and two from Kachemak Bay (Table 4-3). The longest running data set (1989 to 2013; Mearns et al. (2012)) photo documents three sites within WPWS. Three other data sets collected in WPWS include percent cover data from 4 to 10 sites each over periods of 4 to 7 years. Two data sets originated from study sites in Kachemak Bay with the longest covering the period from 1999 to 2013. We used a weight of evidence approach to produce a history of synchronous, large-scale recruitment events (Table 4-7) assuming up to a one-year lag between occurrence of a recruitment event and subsequent peak mussel abundance. Based on these data sets along with our own data presented above, we identified four potential large-scale mussel recruitment events between 1989 and 2013 beginning in 1992, 1997, 2002 and 2007 (Table 4-7).

Table 4-7. Summarization of mussel density data (Lindeberg et al. 1999) or percent cover (all others) from various studies conducted in the GOA from 1989 through 2013. Years in which mussel abundance estimates were available are indicated in yellow or red. Years with anomalously high mussel abundance are indicated in red, while years in which mussel percent cover or density were low are indicated in yellow. Years in which recruitment pulses were observed or inferred from density or percent cover data are highlighted in blue.

Year	WPWS					Kachemak Bay		KEFJ	KATM
	Mearns et al. (2012)	Houghton et al. (1997)	Highsmith et al. (1994)	Lindeberg et al. (1999)	This report	Shigenaka (2014)	Konar and Iken (Unpub.)	This report	This report
1989	Yellow								
1990	Yellow								
1991	Yellow								
1992	Red	Yellow	Red	Blue	Blue	Blue		Blue	Blue
1993	Red	Yellow	Red	Blue	Blue	Blue		Blue	Blue
1994	Yellow			Red					
1995	Yellow			Yellow					
1996	Yellow								
1997	Yellow	Blue	Blue	Blue	Blue	Blue		Blue	Blue
1998	Red	Blue	Blue	Blue	Blue	Blue		Blue	Blue
1999	Yellow					Yellow			
2000	Yellow					Yellow			
2001	Yellow					Yellow			
2002	Red	Blue	Blue	Blue	Blue	Red	Blue	Blue	Blue
2003	Red	Blue	Blue	Blue	Blue	Red	Blue	Blue	Blue
2004	Yellow					Red			
2005	Yellow					Yellow			
2006	Yellow					Yellow			Yellow
2007	Yellow	Blue	Blue	Blue	Red	Yellow		Red	Red
2008	Red	Blue	Blue	Blue	Blue	Yellow		Red	Red
2009	Red					Yellow		Yellow	Yellow
2010	Yellow				Yellow	Yellow		Yellow	Yellow
2011	Yellow				Yellow	Yellow		Yellow	Yellow
2012	Yellow				Yellow	Yellow		Yellow	Yellow
2013	Red				Red	Red		Red	Red

Preliminary examination of possible environmental drivers of large-scale recruitment events

1) Upwelling / downwelling

While the GOA is generally a downwelling system (Weingartner 2005), weak upwelling does occur during summer months. Based on a May/June spawning peak, mussel larvae are generally in the water during neutral or weak upwelling conditions; however, there was no obvious difference in upwelling conditions during peak recruitment years vs. other years (Figure 4-17).

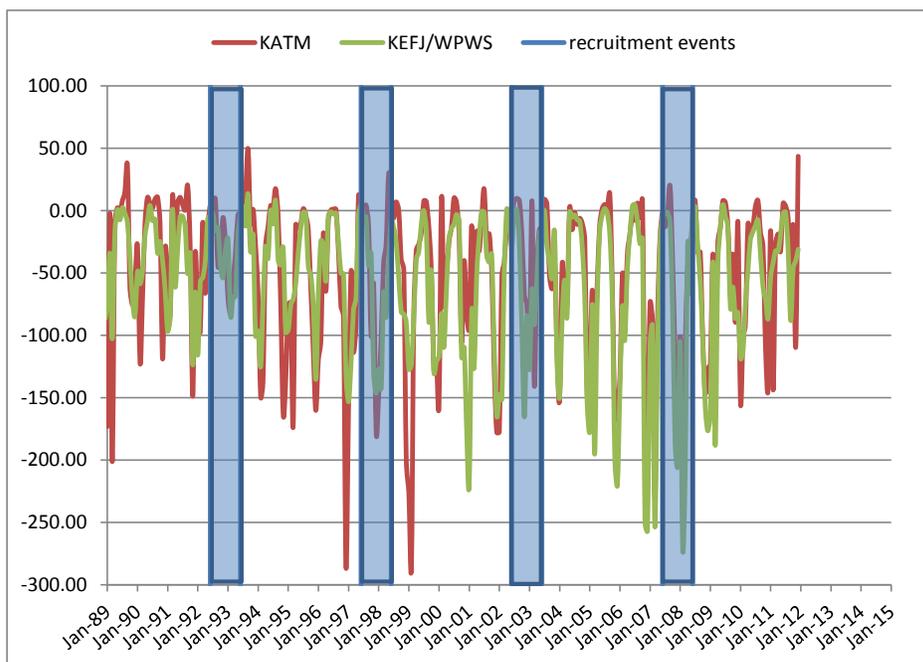


Figure 4-17. Recruitment events occurring in the GOA since 1989 relative to NOAA’s PFEL Global 1-degree Upwelling index. Positive values indicate upwelling conditions while negative values indicate downwelling conditions.

2) Productivity (chlorophyll-a concentrations)

Maximum chlorophyll-a concentrations and anomalies tended to be highest at KATM (max = 10.2 mg m⁻³), and declined to the east (max = 7.5 mg m⁻³ at KEFJ and 4.0 mg m⁻³ in WPWS). We noted that in 2007 (the year we are most confident we identified a large-scale recruitment event), there were anomalously high chlorophyll-a values in Sept/Oct in all three regions (Figure 4-18), although the pattern did not hold for the other recruitment events.

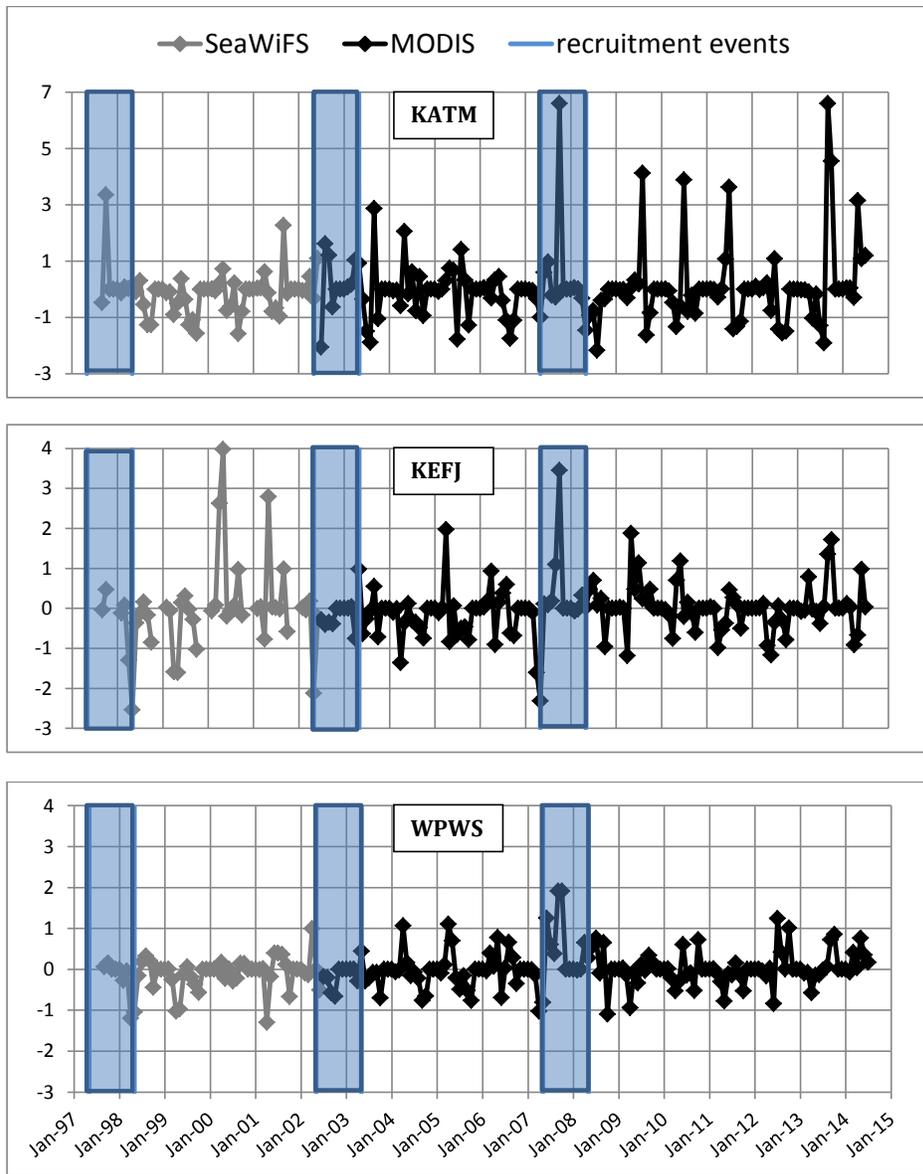


Figure 4-18. Recruitment events occurring in the GOA since 1989 relative to NASA’s satellite derived anomalies in chlorophyll-a data for the KATM area (58.6N-57.8N, 155W-153.8W), KEFJ area (60N-58.5N, 151.5W-149.5W), and the WPWS area (60.8N-59.3N, 148.5W-146.8W). Data for 1997 to 2002 are SeaWiFS 9km and data for 2002 to 2014 are MODIS-Aqua 4km. Note the anomaly scale difference between areas.

3) Freshwater discharge

Spring freshwater discharge into the GOA is important for setting up spring-time upper level stratification layers, the timing of which influences the timing and strength of the spring bloom (Weingartner 2005, Weingartner et al. 2005). While very speculative, it does appear that recruitment peaks occurred after periods of anomalously low 12-month running average discharge rates with possibly anomalously high discharge rates in the summer/fall of the recruitment year though this pattern did not hold for the 1992 recruitment event (Figure 4-19).

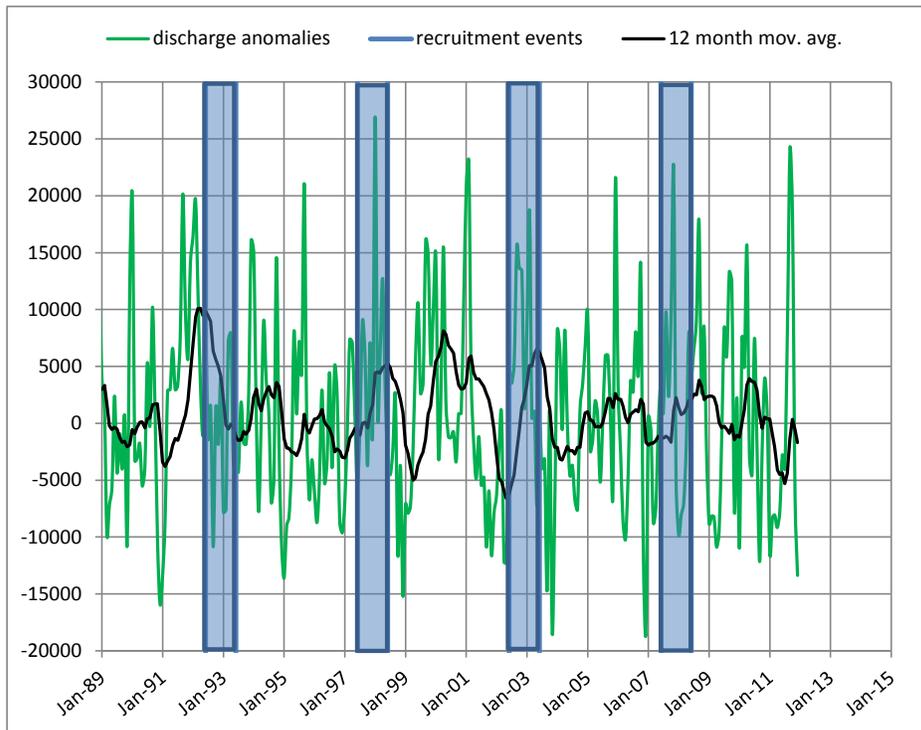


Figure 4-19. Recruitment events occurring in the GOA since 1989 relative to freshwater discharge anomalies along with the 12 month moving average of freshwater discharge from the Alaska coastal freshwater discharge time series.

4) Water temperature and salinity

Spring stratification is monitored through water temperature and salinity profiles that, in turn, indicate conditions suitable for spring and summer phytoplankton blooms. The 2007 recruitment event corresponded with anomalously cool water temperatures at depth (<http://www.ims.uaf.edu/gak1/>) throughout the year with somewhat analogous conditions in 1991 just prior to another identified recruitment event. However, a similar cool water event in 2009 did not appear associated with large-scale mussel recruitment and the recruitment events in 1997 and 2002 occurred with average water temperature profiles. Our identified recruitment pulses may weakly correlate with anomalously cool sea surface temperatures (Figure 4-20).

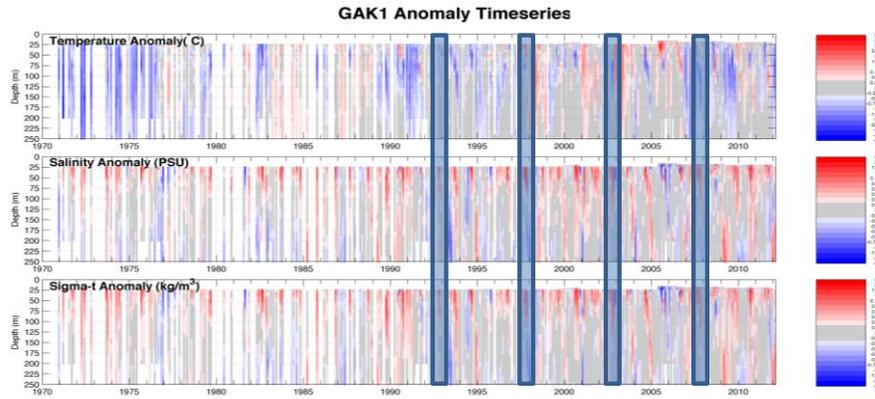


Figure 4-20. Recruitment events occurring in the GOA since 1989 relative to water temperature and salinity anomalies from the GAK1 time series.

5) Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) Index is a long-lived El Niño-like pattern of Pacific climate variability although it refers generally to extended (20-30 years) “warm” and “cool” oceanic regimes. While it is believed that we entered a “cool” regime sometime in the late 1990’s (Peterson & Schwing 2003), the PDO index shifted into generally positive (warm) values between 2002 and 2007 (Figure 4-21). Strong recruitment in 2007 noted over much of our study area was not associated with a strong positive PDO signal. However, we note that large-scale recruitment events do appear to begin near transition periods where the index switches from cool to warm or warm to cool conditions (Figure 4-21).

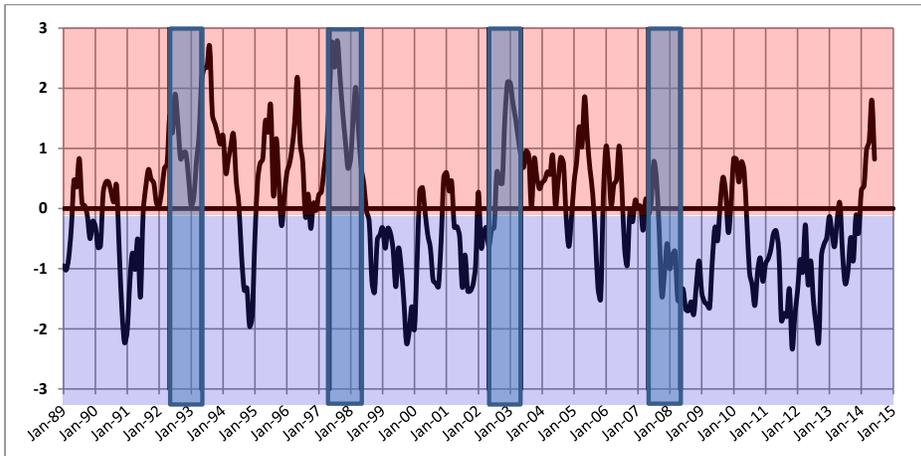


Figure 4-21. PDO index values (<http://jisao.washington.edu/pdo/PDO.latest>) from 1989 to present (positive values indicate “warm” oceanic conditions while negative values indicate “cool” conditions). Blue bars represent estimated periods of strong mussel recruitment in the GOA.

6) El Niño/Southern Oscillation (ENSO)

The El Niño/Southern Oscillation (ENSO) is a coupled ocean-atmosphere phenomenon causing global climate variability on inter-annual time scales. The index corresponds to movement of warm equatorial waters coastward and then northward during El Niño events with the opposite occurring during La Niña conditions. Mussel recruitment events in the GOA do not appear to correlate well with strong El Niño or La Niña events, though similar to the PDO index they may correspond with periods of transition (Figure 4-22).

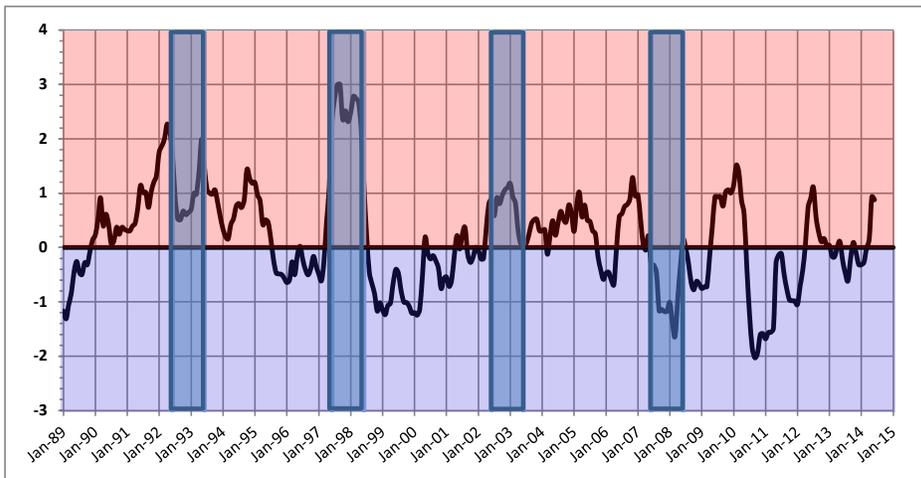


Figure 4-22. ENSO MEI index values (<http://www.esrl.noaa.gov/psd/enso/mei/table.html>) from 1989 to present (positive values indicate “warm” oceanic conditions while negative values indicate “cool” conditions). Blue bars represent estimated periods of strong mussel recruitment in the GOA.

7) North Pacific Gyre Oscillation (NPGO)

Di Lorenzo et al. (2008) assert that “fluctuations in the NPGO are driven by regional and basin-scale variations in wind-driven upwelling and horizontal advection – the fundamental processes controlling salinity and nutrient concentrations.” The NPGO has been shown to correlate with fluctuations in salinity, nutrients and chlorophyll in the North Pacific that were not explainable by PDO (Di Lorenzo et al. 2008). We found the NPGO index did not appear to correspond at all to our identified mussel recruitment events (Figure 4-23). Possibly, this index reflects mid-Gyre dynamics that have little to do with the coastal processes controlling productivity in the GOA.

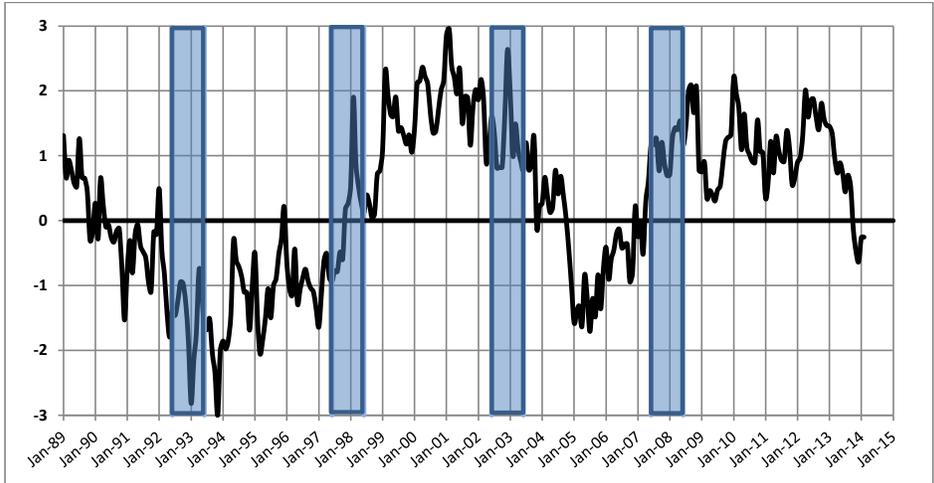


Figure 4-23. NPGO index values (<http://www.o3d.org/npgo/npgo.php>) from 1989 to present. Blue bars represent estimated periods of strong mussel recruitment in the GOA.

8) Northern Oscillation Index (NOI)

The extra-tropical-based Northern Oscillation Index (NOI) and its analog, the Southern Oscillation Index (SOI) are new indices of mid-latitude climate fluctuations, reflecting variability in equatorial and extra-tropical teleconnections and representing a wide range of local and remote climate signals. However, this index did not appear to correspond with large-scale mussel recruitment events in the GOA (Figure 4-24).

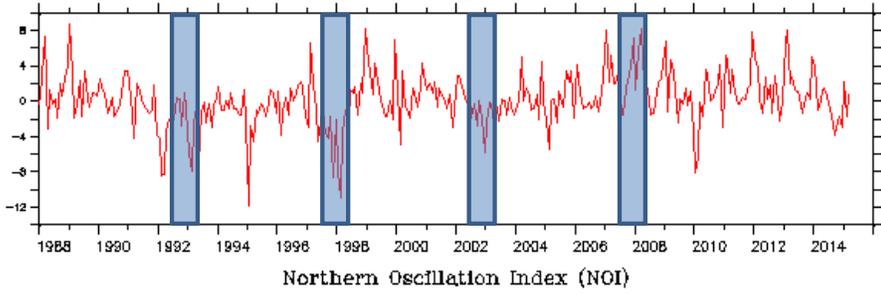


Figure 4-24. NOI index values (http://www.pfeg.noaa.gov/products/PFEL/modeled/indicies/NOIx/data/noix_1988_now) from 1988 to present. Blue bars represent estimated periods of strong mussel recruitment in the GOA.

Discussion

Mussel abundance / size and predator response based on Gulf Watch Alaska data

This synthesis presents a subset of data collected by the nearshore component of the Gulf Watch Alaska long-term ecosystem monitoring program (<http://www.gulfwatchalaska.org/>), which is anticipated to span >20 years. The geographic and temporal scope of this project provides the unique opportunity to examine nearshore benthic processes of the GOA at an ecosystem scale. To date, our Gulf Watch data have indicated one large-scale *M. trossulus* recruitment event in 2007, suggestive of a synchronous recruitment event by *M. trossulus* across our entire northern GOA sampling area, which extends over ~ 500 linear km of coast. Support for a GOA wide recruitment event includes post-recruitment peaks in percent cover of mussels, sizes of mussels and the proportion of mussels in the diets of black oystercatchers and sea otters between 2008 and 2009 with most of these metrics documented at each of our three GOA sites.

Following what appears to have been a large recruitment event in 2007, we observed site-specific declines in percent cover of mussels at randomly selected rocky intertidal sites, suggestive of variable sources of mortality. From their peaks, average mussel cover declined by more than 75% in each of the three regions sampled. The total number of large mussels (≥ 20 mm) available in selected mussel beds also declined through 2013. The average decline in the total number of larger mussels in selected mussel beds ranged from 69% in KEFJ to 98% in KATM over the 5 years of study. In addition, the average size of large mussels declined by 12% across all regions. Variability in timing and rate of decline among sites suggests several mechanisms working at different timescales produced the declines. Likely mechanisms include predation from a suite of both invertebrate (primarily sea stars and predatory whelks) and vertebrate (sea otters, black oystercatchers, Barrow's goldeneye, and harlequin ducks) predators, as well as physical disturbance (wave action, ice scour, and extreme temperatures). While we do not yet have enough information to assess the relative influences of each of these mortality factors at the site-specific level, we are confident in the overall trend of declining mussel abundance within each of the three regions of the north GOA coast. In addition, while core sampling indicated all our sites experienced variable annual recruitment of *M. trossulus*, we are also confident that no other large-scale recruitment event that could replenish mussel stocks at the GOA scale occurred between 2008 and 2013.

The pattern of mussel abundance described here is not unlike patterns of abundance described for another mussel in the Netherland's Wadden Sea (Beukema & Dekker 2007). Beukema and Dekker (2007) followed temporal patterns of *M. edulis* abundance over a period of 26 years and found that it varied greatly. Moreover, recruitment pulses separated by years of recruitment failures were the main cause of variation in their observed mussel abundance patterns. Further, recruitment failure appeared to be a common cause of variation in a number of other bivalve species (Fukuyama 1985, Beukema et al. 2010). Similarly, episodic large-scale recruitment events of *M. edulis* have been documented in the downwelling system of the eastern coast of the United States (Witman et al. 2003). These examples of episodic recruitment are quite different from the paradigm typical of Pacific outer coast studies, which generally includes consistent recruitment and top-down control (Paine 1974).

We also observed the multiplicative effect on overall mussel availability to consumers created by the combination of reductions in mussel body size, bed size, and within bed density, which produced 72% (KEFJ) to 98% (KATM) declines in total energy available from large mussels over 4 to 5 years. At KEFJ in particular, where *M. trossulus* abundance was much higher than at the other two areas, the decline in available mussel energy was coincident with a decline in the proportion of mussels in the diet of at least

two nearshore vertebrate predators (sea otters and black oystercatchers), indicating higher trophic level responses to declines in mussel availability. The overall pattern suggests mussels may be particularly important to vertebrate predators at KEFJ. We do not yet know why *M. trossulus* abundance is higher at KEFJ than our other study areas. However, the importance of mussels to vertebrate predators occupying KEFJ may be explained in part by the generally steep bathymetry of the area and limited availability of shallow subtidal habitats, which presumably would limit availability of alternate prey (e.g., clams) accessible to benthic foraging vertebrate predators. Clams in particular made up an average of only 28% of the sea otter's diet at KEFJ, but this component varied inversely with mussel consumption such that clams made up 13% of their diet at the peak of mussel consumption in 2008 and then increased to 61% of the diet at the low point in mussel consumption in 2012. Presumably, when mussel abundance was high, foraging on mussels was more efficient than foraging on clams at KEFJ.

In contrast, sea otters at KATM rarely consumed mussels and sea otters in WPWS utilized them, but to a much lesser degree than at KEFJ. Both KATM and WPWS have extensive shallow soft-sediment habitats that provide numerous alternate prey species including infaunal clams, which made up an average of 59% and 56% of the diet in these two regions respectively. Thus, it is likely that sea otters showed less of a response to the decline in mussel abundance at KATM and WPWS because of the availability of alternative prey. In addition, the relatively stable size of mussels taken by vertebrate predators is not surprising given that we expect both black oystercatchers and sea otters are size selective predators. The reduction in mean size of large mussels across all of our GOA sites is also likely driven by the size selective foraging patterns of both these and other (e.g., sea duck) predators.

Long-term mussel recruitment patterns

Examination of additional data sets on mussel abundance in the GOA available since 1989 suggests that large-scale mussel recruitment is episodic and may occur about every 5 to 7 years. The peak years of mussel abundance do not line up exactly (see for example the lack of a peak in Kachemak Bay in 2007/2008), but this analysis is suggestive that in the GOA over the past 25 years, peaks in abundance occur infrequently and that, at least in 2007/2008, peak recruitment events may have been synchronous across the GOA. Peak mussel abundances appear to lag strong recruitment events by 1-2 years. We might expect a lag between the onset of a recruitment pulse and peak percent cover of mussels for several reasons. First, initial settlement of mussel plantigrades (newly metamorphosed veligers) measuring 0.26 to 0.29 mm generally occurs on filamentous algae (e.g. *Cladophora* and *Pterosiphonia*) but they can also attach to rocks or larger algae (e.g., *Fucus*). These small mussels generally remain attached to the algae until they reach a size of approximately 1 to 4 mm, approximately 2 months or more after primary settlement. It is important to note that our core sampling generally occurs above the primary settlement zone and thus may not capture the onset of a settlement event. After primary settlement, the mussels often go through a secondary settlement phase, moving to secure attachment surfaces on rock and especially in crevices or among byssal threads of other more mature mussels (Seed 1976). There is direct evidence that mussel movements after primary settlement can be 10s of centimeters to over 100 meters (Hunt & Scheibling 1998, 2002, Petrovic & Guichard 2008), with longer range movements possible when small mussels are carried about while attached to drift algae. Some limited mobility of *M. trossulus* can persist through the first year or two years after secondary settlement, when mussels reach about 10 mm (Feder & Keiser 1980). Thus, GWA sampling will only reflect recruitment success after the secondary settlement process is complete. In addition to secondary settlement, percent cover by mussels may increase after settlement simply because of mussel growth. Lag times probably vary from site to site based on the exact

timing of recruitment and survey dates, the relative strength of the recruitment, growth rates of mussels at a site, and influences of secondary settlement on juvenile mussel survival. While there are clear limitations with respect to the interpretation of these data sets, they suggest that over the past 25 years, there were at least regional recruitment peaks at multiple sites in 1992, 1997, 2002, and 2007.

The regularity of these events could indicate a predictable, cyclical pattern possibly driven by some demographic relationship within the mussel populations themselves. For example, large mussels produce more propagules than smaller mussels implying that larval supply increases as the pulse of new recruits increase in size, and a new pulse of recruitment may occur after the prior pulse of recruits matures. However, we observed the highest density of the largest mussels one to two years after the 2007 recruitment event. This suggests production of propagules is not the limiting factor during low recruitment years for *M. trossulus* in the GOA. Alternatively, the patterns in mussel recruitment, abundance and predator responses we observed across the Gulf of Alaska in this study suggest the GOA is a system under supply-side control. Further, episodic *M. trossulus* recruitment pulses suggest large-scale oceanographic processes may drive variation in recruitment, and that oceanographic conditions favorable for recruitment are uncommon. Specifically, local, regional or GOA-wide scale ocean conditions may be important in determining annual recruitment levels and when optimum conditions are present across regions, could appear as broader scale patterns. A primary objective of further analysis will be to clarify the spatial scales at which mussel recruitment occurs.

Potential drivers of M. trossulus recruitment in the GOA

The Gulf of Alaska is characterized by downwelling conditions (Mundy 2005) with spring productivity blooms linked to a complex, multi-step process that begins with conditions that favor onshore movement of nutrient rich deep slope water during the previous summer, good mixing during fall/winter, and freshwater driven stratification of surface waters in spring (Weingartner 2005). It is also evident that in the predominantly downwelling system in the GOA, the strength and timing of the spring bloom is not as closely coupled with the solar cycle as in predominately upwelling systems in mid latitudes such as along the coasts of Oregon or Washington (Weingartner et al. 2005). As a result, the presence of a strong spring bloom is not as predictable in the GOA as in lower latitudes. This difference may contribute to the lower predictability of successful mussel recruitment in the GOA.

Shigenaka (2014) suggested that peak mussel abundances (i.e., greater than the long-term mean) in Kachemak Bay occurred during positive (warm) PDO and low mussel abundances occurred during negative (cool) PDO. However, the correlation is less apparent when a broader geographic view of recruitment patterns is adopted (Figure 4-18). We did not identify high mussel abundances during the generally warm period of 1995-1997, and GWA data identified a period of peak mussel abundance (2007 to 2009) occurred during a cool period. Generally, the timing of recruitment events appeared to correlate only weakly if at all to the eight environmental drivers we examined. Specifically, we found no apparent correlation between recruitment events and indices of upwelling strength, ENSO, NPGO, and NOI. Relationships with indices of chlorophyll-a concentrations, freshwater discharge, water temperature and salinity profiles and PDO were weak at best. However, our visual analysis was only exploratory in nature and a rigorous analysis is required before we can discount any of these drivers. In addition, the lack of visual correlations may also be due, in part, to the difficulty of obtaining data that accurately reflect nearshore oceanographic conditions. For example, suspended material from glacial and river run-off is known to produce anomalous readings in satellite derived chlorophyll-a concentration measurements.

The lack of a relation between periods of significant mussel recruitment and the potential drivers we examined suggests at least three possibilities. 1) Our assessments of what years produced large-scale recruitment events are not completely accurate due to limitations in the historical data sets. 2) Local physical and oceanographic conditions as well as annual variation in larval source and transport corridors (Fodrie et al. 2011) control site specific mussel recruitment success, and large-scale recruitment events occur coincidental to when many sites across the GOA happen to have favorable conditions in the same year. 3) Large-scale oceanic conditions are important, however they interact in a complicated manner to generate strong mixed-layer development that enhances nutrient supply, promotes spring blooms, and presumably leads to strong mussel recruitment events, so that no one driver adequately captures the conditions that favor strong mussel recruitment success. Weingartner (2005) hypothesized that “mixed-layer development (and the associated pulse of nutrients) depends on processes spanning a range of time scales and involves a plethora of variables that affect vertical mixing and the offshore flux of freshwater from the nearshore”. The variables include the relative amounts of winter rain and snow, the timing of snowmelt, and wind velocity. The relevant time scales might range from a few days (for storm events) to many months. Thus, finding associations between physical factors and mussel recruitment might require a rather complicated model that relates the timing and strength of multiple physical factors with timing and strength of the spring plankton bloom. At this time, we cannot discount any of the three explanations for the weak correlations between oceanographic drivers and recruitment events; however, there is an extensive literature (highlighted below) that suggests the third explanation merits careful consideration.

Implications of episodic recruitment driven by large-scale oceanic conditions

We hypothesize that the lack of a consistent spring bloom in the GOA may explain much of the variation in large-scale mussel recruitment in the GOA. If true, inconsistent spring blooms may also influence recruitment patterns in other invertebrates with planktonic larvae such as sea urchins (*Strongylocentrotus drobachiensis*), littleneck clams (*Leukoma staminea*), and possibly some sea stars (e.g., *Pisaster ochraceus* and *Pycnopodia helianthoides*), and this may result in notable differences between the GOA and those systems more dominated by upwelling. For example, it has been widely observed in upwelling dominated systems that removal of sea otters can lead to a strong and sudden increase in dominance by sea urchins (Estes & Palmisano 1974, Palmisano & Estes 1977, Estes et al. 1978, Estes & Duggins 1995). In contrast, Dean et al. (2000) found little response in sea urchin populations following a drastic reduction in the number of sea otters in PWS after the *Exxon Valdez* oil spill, and speculated that the lack of a response was the result of lack of predictable recruitment by sea urchins. Similarly, Estes et al. (2010) note a discontinuity in sea urchin abundance and apparent recruitment at the Islands of Four Mountains in the Aleutian chain. West of this discontinuity, the nearshore zones of the islands are essentially oceanic in character and annual urchin recruitment appears strong. East of the discontinuity, the islands are on the Continental Shelf; urchin recruitment appears to be sporadic and less consistent from year to year with the result that even with an apparent reduction in sea otter abundance, macro algae were still common and subtidal habitats did not become “urchin barrens”. Sharp discontinuities of this nature have also been documented in upwelling systems along the west coast of the US (Blanchette & Gaines 2007, Blanchette et al. 2007, Broitman et al. 2008). The decline in littleneck clams observed within the GOA over the past decades also appears related to a lack of recruitment (Shigenaka 2014).

While mussel recruitment pulses were observed over a wide geographic range in 2007/2008, strong recruitment does not appear to be the norm. In addition to the high inter-annual variation in the strength of the spring bloom in the GOA, there is also evidence that there is spatial discontinuity in the timing and

strength of the bloom and possibly mussel recruitment over the GOA. Preliminary evidence suggests that the bloom is initiated in early spring in PWS and then radiates out of the Sound and onto the shelf over the next four to six weeks (Weingartner 2005, Weingartner et al. 2005). In addition, the spread of the bloom may not proceed simultaneously over the entire shelf. Furthermore, there is evidence that while the entire GOA is primarily a downwelling system, that upwelling also occurs and may be stronger in some parts of the Gulf than elsewhere (http://www.pfeg.noaa.gov/products/las/docs/global_upwell.html). Means of monthly indices of upwelling for example appear to be stronger along the Katmai coast than in PWS. While there was evidence of GOA wide pulses of recruitment in 2007, the possible discontinuity in the intensity of upwelling may help to explain anomalies in this pattern such as the relative lack of mussel recruitment observed in Kachemak Bay in 2007/2008 and the evidence of significant recruitment at KATM in 2010.

The spatial and temporal variation in recruitment by mussels and possibly other invertebrates in the GOA compared to upwelling systems may have implications with respect to the relative influence of top down (i.e., predation and physical disturbance) vs. bottom up (larval supply) control of community structure. In upwelling systems with predictable and presumably non-limiting mussel recruitment, top-down mechanisms can dominate control of mussel abundance at local scales (Paine 1966, 1969, 1977, Menge 1991, Menge et al. 1997, Menge 2000). In contrast, the GOA system appears to vary between periods following strong mussel recruitment that are dominated by bottom-up control vs. years in the absence of strong mussel recruitment when top-down forces dominate. The implication of variable mussel recruitment includes community-level effects such as reduced importance of predators in controlling long-term mussel population dynamics (Menge 1991, Robles 1997, Menge 2000), trophic cascades (Witman et al. 2003) and local adaptation to fluctuating resources (Sanford & Worth 2010). Moreover, without significant annual recruitment, the loss of mussel-based energy to predators (especially size selective vertebrate predators) was relatively rapid, with 70% or greater losses over a period of only 3-5 years.

Long-term implications of sporadic recruitment events

Nearshore marine systems have proven to be excellent laboratories for the study of community ecology and population dynamics (Robles & Desharnais 2002). Examples of seminal field studies originating in nearshore ecosystems include studies of space competition (Connell 1961b, a, Dayton 1971, 1975) and the cascading “top-down” effects of predation on community composition and structure (Paine 1966, 1969, Estes & Palmisano 1974, Paine 1974, 1976, Estes et al. 1978, Estes & Duggins 1995). More recently, the importance of nearshore-pelagic coupling of trophic food webs on nearshore community structure has come to light (Estes et al. 1998, Springer et al. 2003, Estes et al. 2004). Further, “supply-side” concepts originated in nearshore systems (Gaines et al. 1985, Gaines & Roughgarden 1985, Lewin 1986, Roughgarden et al. 1988, Underwood & Fairweather 1989, Grosberg & Levitan 1992, Underwood & Keough 2001, Robles & Desharnais 2002, Lee & Bruno 2009).

Importantly, the supply and survival of invertebrate propagules may be coupled to large-scale variations in oceanic conditions (Menge 2000, Menge et al. 2003, Navarrete et al. 2005, Broitman et al. 2008, Menge et al. 2009), although these linkages are far from clear (Schiel 2004). In turn, the population dynamics and productivity of higher trophic level nearshore vertebrate predators may be influenced by variation in their intertidal invertebrate prey populations (Robles 1997, Witman et al. 2003, Hipfner & Elnor 2013). Thus, within recruitment-limited systems in particular, supply-side ecological concepts link

broad-scale physical drivers to ecosystem productivity, the population dynamics of its component species, and the trophic linkages among those species, which may have broader implications for persistence and resilience in nearshore community structure. Trophic linkages imply that variation in intertidal prey communities may have important effects on performance and population dynamics of important consumers such as sea otters, sea ducks and oystercatchers. If benthic-pelagic coupling exists as described above, changes in nearshore communities (including nearshore predator communities) may occur as climate change influences oceanographic conditions in the future. Our ability to predict how climate change may influence nearshore communities will be enhanced by a fuller understanding of the mechanisms that couple pelagic and nearshore benthic systems.

While our focus in this report has largely been on broad geographic scale patterns, during the 2007 recruitment event, there was considerable spatial variation in recruitment when viewed on smaller spatial scales. For example, at randomly selected rocky intertidal sites, we observed percent cover of mussels of greater than 25% at only five of 15 sites in KATM, KEFJ, and WPWS. We speculate that spatial discontinuities in the spring bloom, along with vagaries of spatial patterns in larval dispersal and post-settlement survival may help to explain this smaller scale spatial variation.

Conclusions

In this section, we highlight a number of patterns in mussel population dynamics that emerge from examination of the nearshore component data collected as part of Gulf Watch Alaska, in concert with consideration of other available data sets from the north Gulf of Alaska region that pre-date Gulf Watch. Key findings include:

1. There is good evidence that *M. trossulus* does not recruit consistently in the GOA. Specifically, intense recruitment events occur on an episodic basis with some degree of synchronicity across broad spatial scales, while some degree of mussel recruitment and settlement occurs annually at a site-specific level, but below levels able to maintain mussel biomass.
2. After strong large-scale recruitment pulses, mussel abundance and biomass tend to decline over time, presumably due to predation and disturbance events, but the extent and timing of declines appears to be locally variable.
3. Predators respond to variation in mussel abundance and biomass by changing their use of mussels.
4. Oceanographic or climatic drivers of synchronous broad-scale mussel recruitment events are unclear; examination of a number of indices did not reveal correlative relationships.
5. Dynamics of *M. trossulus* in protected waters of the north Gulf of Alaska may be driven by different forces than that of *M. californianus* along open coasts of more southern latitudes.
6. Additional understanding of the factors driving variation in mussel populations and the effects on mussel consumers will be facilitated by continued monitoring as part of Gulf Watch Alaska, along with directed research to understand functional relationships among ecosystem components.

Considerations for Future Directions

From this analysis of 2006-2013 GWA data in conjunction with other available datasets, we have identified important patterns that further our understanding of the dynamics of mussel (and possibly other intertidal species) populations in the GOA. Continued monitoring and quantitatively integrated analyses

will advance our understanding of the structure and function of the nearshore community. As a consequence, alternative approaches to further synthesis can be generated from our results to date. One approach will be to continue to evaluate the assumption that ocean and environmental factors control the recruitment of mussels at the regional or GOA spatial scales. Another approach will be to evaluate the assumption that mussel recruitment occurs regularly, although at varying magnitude, at the spatial scale of sites or regions. And lastly, we will continue to explore, through quantitative modeling, the effect of varying energy density provided by mussels to the performance of vertebrate consumers. Specifically, we can generate a list of viable hypotheses as a result of work to date:

1. Compared with mid-latitude upwelling systems, the predominately downwelling environment in the GOA has less frequent and less predictable blooms of phytoplankton that result in less frequent and less predictable recruitment of mussels and potentially other invertebrates.
2. Inter-annual variation in mussel settlement and recruitment success largely drives mussel population dynamics in the GOA (i.e., mussels are recruitment limited in the GOA).
3. Because mussels in the GOA are recruitment limited, and because mussels have a profound effect on the intertidal community dynamics and on the predators that rely on these communities, the timing and strength of mussel recruitment has influences that are propagated through the larger nearshore system.
4. Successful recruitment years for mussels, and potentially other invertebrates with planktonic larval stages, are linked to;
 - a. Timing and strength of spring bloom that promotes good larval growth and survival. The timing and strength of the spring bloom is in turn reliant on a complex combination of physical factors (fresh-water input and wind velocity).
 - or
 - b. Local physical factors such as variation in larval sources, larval transport corridors and site-specific juvenile mussel survival control large-scale recruitment events coincidentally when many sites happen to experience conditions favorable to strong mussel recruitment in the same year.
5. Because of variable recruitment of mussels, the relative strength of bottom-up and top-down controls on the intertidal community in the GOA vary over time. During periods of strong mussel recruitment, the community is primarily influenced by bottom-up forces (i.e., mussel recruitment success). During other times, the system is largely controlled by top-down forces (predation and physical disturbance). This is in contrast to upwelling systems where the relative influences of top-down and bottom-up controls are more consistent over time.
6. Because large-scale, strong mussel recruitment events may be driven by large-scale oceanographic conditions, we may be able to make predictions as to the effect climate change may have on frequency and strength of mussel (invertebrate) recruitment levels in the future along with the potential population dynamics and trophic consequences it may have. However,

predictions will depend on modeling the complex linkages between physical processes (large and small scale) and GOA productivity and recruitment patterns.

7. For higher trophic level species largely dependent on mussels (e.g., Barrow's goldeneye), we might expect tight coupling of performance metrics and mussel abundance. For species for which mussels can be a substantial component of the diet but that have more latitude in utilizing alternative prey (e.g., harlequin ducks, black oystercatchers), we might expect looser coupling of performance metrics and mussel abundance. The sea otter in particular may be an informative contrast as in most areas of the GOA, mussels are a relatively small component of their diet and we might expect mussel abundance to have little effect on performance metrics (though mussels may be important to juvenile survival; VanBlaricom (1988)). However, data presented here indicate sea otters at KEFJ utilize mussels to a much higher degree when available, and we may expect to see mussel abundance having significant effects on sea otter performance metrics in this location.

Continued sampling in the nearshore system through the Nearshore Benthic component of Gulf Watch Alaska, along with the development of more sophisticated oceanographic models that can predict the strength and timing of spring phytoplankton blooms, will provide further data for testing these hypotheses. Of particular importance will be the data from 2014 and beyond. In the early summer of 2014, we observed the first strong, broad-scale year for mussel recruitment since 2007. High densities of newly recruited mussels were widely observed throughout KATM and KEFJ, and at selected locations in WPWS. The biological and physical data collected in 2014 and in future years will provide further understanding of mussel population dynamics, their relation to physical factors, and on their broader influence on the nearshore system in general, and possibly in response to a predicted El Niño event unfolding in 2014 specifically. If the 2014 recruitment event proves to be successful, it also provides the opportunity to initiate directed studies focused on documenting changes in selected nearshore vertebrate predator performance metrics as they live through another cycle of high and then diminishing mussel availability.

References

- Anderson EM, Lovvorn JR (2012) Seasonal dynamics of prey size mediate complementary functions of mussel beds and seagrass habitats for an avian predator. *Mar Ecol Prog Ser* 467:219-232
- Andres BA (1999) Effects of Persistent Shoreline Oil on Breeding Success and Chick Growth in Black Oystercatchers. *The Auk* 116:640-650
- Bayne BL (1976) *The biology of mussel larvae*. Cambridge University Press, New York
- Beukema JJ, Dekker R (2007) Variability in annual recruitment success as a determinant of long-term and large-scale variation in annual production of intertidal Wadden Sea mussels (*Mytilus edulis*). *Helgol Mar Res* 61:71-86
- Beukema JJ, Dekker R, Philippart CJM (2010) Long-term variability in bivalve recruitment, mortality, and growth and their contribution to fluctuations in food stocks of shellfish-eating birds. *Mar Ecol Prog Ser* 414:117-130
- Blanchard A, Feder HM (1997) Reproductive timing and nutritional storage cycles of *Mytilus trossulus* Gould, 1850, in Port Valdez, Alaska, site of a marine oil terminal. *Veliger* 40:121-130
- Blanchette CA, Gaines SD (2007) Distribution, abundance, size and recruitment of the mussel, *Mytilus californianus*, across a major oceanographic and biogeographic boundary at Point Conception, California, USA. *J Exp Mar Biol Ecol* 340:268-279
- Blanchette CA, Helmuth B, Gaines SD (2007) Spatial patterns of growth in the mussel, *Mytilus californianus*, across a major oceanographic and biogeographic boundary at Point Conception, California, USA. *J Exp Mar Biol Ecol* 340:126-148
- Broitman BR, Blanchette CA, Menge BA, Lubchenco J, Krenz C, Foley M, Raimondi PT, Lohse D, Gaines SD (2008) Spatial and temporal patterns of invertebrate recruitment along the West Coast of the United States. *Ecological Monographs* 78:403-421
- Calkins DG (1978) Feeding behaviour and major prey species of sea otter, *Enhydra lutris*, in Montague Strait, Prince William Sound, Alaska. *Fish Bull* 76:125-131
- Cayford JT, Goss-Custard JD (1990) Seasonal changes in the size selection of mussels, *Mytilus edulis*, by oystercatchers, *Haematopus ostralegus*: an optimality approach. *Anim Behav* 40:609-624
- Coats DA, Imamura E, Fukuyama AK, Skalski JR, Kimura S, J. S (1999) Monitoring of biological recovery of Prince William Sound intertidal sites impacted by the *Exxon Valdez* oil spill. NOAA Technical Memorandum NOS OR&R 1, Seattle, WA
- Connell JH (1961a) Effects of competition, predation by *Thais lapillus*, and other factors on natural populations of the barnacle *Balanus balanoides*. *Ecological Monographs* 31:61-104
- Connell JH (1961b) The influence of interspecific competition and other factors on the distribution of the barnacle *Chthamalus stellatus*. *Ecology* 42:710-723
- Connolly SR, Menge BA, Roughgarden J (2001) A latitudinal gradient in recruitment of intertidal invertebrates in the northeast Pacific Ocean. *Ecology* 82:1799-1813
- Dayton PK (1971) Competition, disturbance, and community organization: the provision and subsequent utilization of space in a rocky intertidal community. *Ecological Monographs* 41:351-389
- Dayton PK (1975) Experimental evaluation of ecological dominance in a rocky intertidal algal community. *Ecological Monographs* 45:137-159
- Dean TA, Bodkin JL, Fukuyama AK, Jewett SC, Monson DH, O'Clair CE, VanBlaricom GR (2002) Food limitation and the recovery of sea otters following the 'Exxon Valdez' oil spill. *Mar Ecol Prog Ser* 241:255-270
- Dean TA, Bodkin JL, Jewett SC, Monson DH, Jung D (2000) Changes in sea urchins and kelp following a reduction in sea otter density as a result of the *Exxon Valdez* oil spill. *Mar Ecol Prog Ser* 199:281-291
- Di Lorenzo E, Schneider N, Cobb KM, Franks PJS, Chhak K, Miller AJ, McWilliams JC, Bograd SJ, Arango H, Curchitser E, Powell TM, Riviere P (2008) North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys Res Lett* 35

- Doroff AM, DeGange AR (1994) Sea otter, *Enhydra lutris*, prey composition and foraging success in the northern Kodiak Archipelago. *Fish Bull* 92:704-710
- Esler D, Bowman TD, Trust KA, Ballachey BE, Dean TA, Jewett SC, O'Clair CE (2002) Harlequin duck population recovery following the 'Exxon Valdez' oil spill: progress, process and constraints. *Marine Ecology-Progress Series* 241:271-286
- Estes JA, Bodkin JL, Tinker MT (2010) Threatened southwest Alaska sea otter stock: Delineating the causes and constraints to recovery of a keystone predator in the North Pacific Ocean. North Pacific Research Board Final Report, Book 717. North Pacific Research Board
- Estes JA, Danner EM, Doak DF, Konar B, Springer AM, Steinberg PD, Tinker MT, Williams TM (2004) Complex trophic interactions in kelp forest ecosystems. *Bull Mar Sci* 74:621-638
- Estes JA, Duggins DO (1995) Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. *Ecological Monographs* 65:75-100
- Estes JA, Palmisano JF (1974) Sea otters: Their role in structuring nearshore communities. *Science* 185:1058-1060
- Estes JA, Smith NS, Palmisano JF (1978) Sea otter predation and community organization in the western Aleutian Islands, Alaska. *Ecology* 59:822-833
- Estes JA, Tinker MT, Williams TM, Doak DF (1998) Killer whale predation on sea otters linking oceanic and nearshore ecosystems. *Science* 282:473-476
- Feder HM, Keiser GE (1980) Intertidal Biology. Port Valdez, Alaska: Environmental Studies 1976-1979, Chapter 8. Occasional Publication
- Fodrie FJ, Becker BJ, Levin LA, Gruenthal K, McMillan PA (2011) Connectivity clues from short-term variability in settlement and geochemical tags of mytilid mussels. *Journal of Sea Research* 65:141-150
- Fukuyama AK (1985) The effects of sea star and walrus predation on bivalves in Norton Sound, Alaska. M.A., San Francisco State University,
- Gaines S, Brown S, Roughgarden J (1985) Spatial Variation in Larval Concentrations as a Cause of Spatial Variation in Settlement for the Barnacle, *Balanus glandula*. *Oecologia* 67:267-272
- Gaines S, Roughgarden J (1985) Larval settlement rate: A leading determinant of structure in an ecological community of the marine intertidal zone. *Proceedings of the National Academy of Sciences* 82:3707-3711
- Garza C (2005) Prey productivity effects on the impact of predators of the mussel, *Mytilus californianus* (Conrad). *J Exp Mar Biol Ecol* 324:76-88
- Goudie RI, Ankney CD (1986) Body size, activity budgets, and diets of sea ducks wintering in Newfoundland. *Ecology*:1475-1482
- Grosberg RK, Levitan DR (1992) For Adults Only? Supply-side Ecology and the History of Larval Biology. *Trends in Ecology & Evolution* 7:130-133
- Gutt J (2001) On the direct impact of ice on marine benthic communities, a review. *Polar Biol* 24:553-564
- Hartwick EB (1976) Foraging strategy of the black oyster catcher (*Haematopus bachmani* Audubon). *Can J Zool* 54:142-155
- Highsmith RC, Stekoll MS, Barber WE, Deysher L, McDonald L, Strickland D, Erickson WP (1994) Comprehensive assessment of coastal habitat. *Exxon Valdez* oil spill state/federal natural resource damage assessment. Final report of coastal habitat study 1A. Exxon Valdez Oil Spill Trustee Council, Anchorage, AK
- Hipfner JM, Elnor RW (2013) Sea-surface temperature affects breeding density of an avian rocky intertidal predator, the black oystercatcher *Haematopus bachmani*. *J Exp Mar Biol Ecol* 440:29-34
- Houghton JP, Lees DC, Driskell WB, Lindstrom SC (1997) Long-term recovery (1989-1996) of Prince William Sound littoral bioata following the *Exxon Valdez* oil spill and subsequent shoreline treatment. In: NOAA (ed). National Oceanic and Atmospheric Administration, Seattle, WA
- Hunt HL, Scheibling RE (1996) Physical and biological factors influencing mussel (*Mytilus trossulus*, *M. edulis*) settlement on a wave-exposed rocky shore. *Mar Ecol Prog Ser* 142:135-145

- Hunt HL, Scheibling RE (1998) Spatial and temporal variability of patterns of colonization by mussels (*Mytilus trossulus*, *M-edulis*) on a wave-exposed rocky shore. *Mar Ecol Prog Ser* 167:155-169
- Hunt HL, Scheibling RE (2002) Movement and wave dislodgment of mussels on a wave-exposed rocky shore. *Veliger* 45:273-277
- Klinger T, Fukuyama AK (2011) Decadal-scale dynamics and response to pulse disturbance in the intertidal rockweed *Fucus distichus* (*Phaeophyceae*). *Marine Ecology* 32:313-319
- Lee SC, Bruno JF (2009) Propagule supply controls grazer community structure and primary production in a benthic marine ecosystem. *Proceedings of the National Academy of Sciences* 106:7052-7057
- Levinton JS, Koehn RK (1976) Population genetics of mussels. Cambridge University Press, New York
- Lewin R (1986) Supply-Side Ecology. *Science* 234:25-27
- Lindeberg MR, O'Clair CE, Saupe SM (1999) Long-term changes in the abundance and growth of the Pacific Blue Mussel, *Mytilus trossulus*, in a heavily oiled bay in Prince William Sound. Appendix SO-03.2 In: Holland-Bartels, L.E. (ed) Mechanisms of impact and potential recovery nearshore vertebrate predators following the 1989 Exxon Valdez oil spill. Exxon Valdez Trustee Council, Anchorage, AK
- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78:1069-1079
- McDonald T (2004) GRTS for the average Joe: A GRTS sampler for Windows. Western EcoSystems Technology, Cheyenne, Wyoming Available: west-inc.com(July 2007)
- Mearns AJ, Lindeberg M, Janka D, Whitney J, Shigenaka G (2012) Twenty-three Year Update of Shoreline Biological Observations in Prince William Sound. Alaska Marine Science Symposium, Anchorage, AK
- Meire PM, Eryvynck A (1986) Are oystercatchers (*Haematopus ostralegus*) selecting the most profitable mussels (*Mytilus edulis*)? *Anim Behav* 34:1427-1435
- Menge BA (1991) Relative importance of recruitment and other causes of variation in rocky intertidal community structure. *J Exp Mar Biol Ecol* 146:69-100
- Menge BA (2000) Top-down and bottom-up community regulation in marine rocky intertidal habitats. *J Exp Mar Biol Ecol* 250:257-289
- Menge BA, Chan F, Nielsen KJ, Lorenzo ED, Lubchenco J (2009) Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment. *Ecological Monographs* 79:379-395
- Menge BA, Daley BA, Wheeler PA, Dahlhoff E, Sanford E, Strub PT (1997) Benthic-pelagic links and rocky intertidal communities: Bottom-up effects on top-down control? *Proceedings of the National Academy of Sciences* 94:14530-14535
- Menge BA, Lubchenco J, Bracken MES, Chan F, Foley MM, Freidenburg TL, Gaines SD, Hudson G, Krenz C, Leslie H, Menge DNL, Russell R, Webster MS (2003) Coastal oceanography sets the pace of rocky intertidal community dynamics. *Proceedings of the National Academy of Sciences* 100:12229-12234
- Mundy PR (2005) The Gulf of Alaska: biology and oceanography. Alaska Sea Grant College Program
- Navarrete SA, Wieters EA, Broitman BR, Castilla JC (2005) Scales of benthic-pelagic and the intensity of species interactions: From recruitment limitation to top-down control. *Proceedings of the National Academy of Sciences* 102:18046-18051
- Nybakken JW (1969) Pre-earthquake intertidal ecology of Three Saints Bay, Kodiak Island, Alaska. University of Alaska. Institute of Arctic Biology
- O'Clair CE, Zimmerman ST (1986) Biogeography and ecology of the intertidal and shallow subtidal communities. In: Hood DW, Zimmerman ST (eds) *The Gulf of Alaska: physical environment and biological resources*. National Oceanic and Atmospheric Administration, Anchorage, AK
- O'Clair RM, O'Clair CE (1998) *Southeast Alaska's Rocky Shores: Animals*. Plant Press, Auke Bay, AK
- Paine RT (1966) Food Web Complexity and Species Diversity. *The American Naturalist* 100:65-75
- Paine RT (1969) A note on trophic complexity and community stability. *Am Nat* 103:91-93

- Paine RT (1974) Intertidal community structure: experimental studies on the relationship between a dominant competitor and its principal predator. *Oecologia* 15:93-120
- Paine RT (1976) Size-limited predation: an observational and experimental approach with the *Mytilus-Pisaster* interaction. *Ecology* 57:858-873
- Paine RT Controlled manipulations in the marine intertidal zone and their contributions to ecological theory. *Proc Proceedings of the Academy of Natural Sciences*
- Palmisano JF, Estes JA (1977) Ecological Interactions Involving the Sea Otter. In: Merritt ML, Fuller RG (eds) *The Environment of Amchitka Island Alaska*. Technical Information Center, US Energy Research and Development Administration, Springfield, VA
- Peterson WT, Schwing FB (2003) A new climate regime in northeast pacific ecosystems. *Geophys Res Lett* 30
- Petrovic F, Guichard F (2008) Scales of *Mytilus* spp. population dynamics: importance of adult displacement and aggregation. *Mar Ecol Prog Ser* 356:203-214
- Phillips NE (2004) Variable timing of larval food has consequences for early juvenile performance in a marine mussel. *Ecology* 85:2341-2346
- Robertson GJ, Goudie RI (1999) Harlequin Duck (*Histrionicus histrionicus*). *The Birds of North America*. The American Ornithologists Union and the Academy of Natural Sciences, Washington, DC and Philadelphia
- Robles CD (1997) Changing recruitment in constant species assemblages: Implications for predation theory in intertidal communities. *Ecology* 78:1400-1414
- Robles CD, Desharnais R (2002) History and Current Development of a Paradigm of Predation in Rocky Intertidal Communities. *Ecology* 83:1521-1536
- Roughgarden J, Gaines S, Possingham H (1988) Recruitment Dynamics in Complex Life-cycles. *Science* 241:1460-1466
- Sanford E, Worth DJ (2010) Local adaptation along a continuous coastline: Prey recruitment drives differentiation in a predatory snail. *Ecology* 91:891-901
- Schiel DR (2004) The structure and replenishment of rocky shore intertidal communities and biogeographic comparisons. *J Exp Mar Biol Ecol* 300:309-342
- Seed R (1976) *Ecology*. Cambridge University Press, New York
- Seed R, Suchanek TH (1992) Population and community ecology of *Mytilus*. In: Gosling (ed) *The mussel Mytilus: ecology, physiology, genetics and culture*, Book 25. Elsevier, Amsterdam
- Shigenaka G (2014) Twenty-Five Years After the *Exxon Valdez* Oil Spill. In: NOAA's Scientific Support M, and Research (ed). NOAA Office of Response and Restoration, Seattle, WA
- Smith JR, Fong P, Ambrose RF (2009) Spatial patterns in recruitment and growth of the mussel *Mytilus californianus* (Conrad) in southern and northern California, USA, two regions with differing oceanographic conditions. *Journal of Sea Research* 61:165-173
- Springer AM, Estes JA, van Vliet GB, Williams TM, Doak DF, Danner EM, Forney KA, Pfister B (2003) Sequential megafaunal collapse in the North Pacific Ocean: An ongoing legacy of industrial whaling? *Proceedings of the National Academy of Sciences* 100:12223-12228
- Stevens Jr DL, Olsen AR (2004) Spatially balanced sampling of natural resources. *Journal of the American Statistical Association* 99:262-278
- Suchanek TH (1986) Mussels and their role in structuring rocky shore communities. In: Moore PG, Seed R (eds) *The Ecology of Rocky Coasts*. Columbia University Press, New York
- Trust KA, Esler D, Woodin BR, Stegeman JJ (2000) Cytochrome P450 1A induction in sea ducks inhabiting nearshore areas of Prince William Sound, Alaska. *Marine Pollution Bulletin* 40:397-403
- Underwood AJ, Fairweather PG (1989) Supply-side Ecology and Benthic Marine Assemblages. *Trends in Ecology & Evolution* 4:16-20
- Underwood AJ, Keough MJ (2001) Supply-side ecology: The nature and consequences of variations in recruitment of intertidal organisms. In: Bertness MD, Gaines SD, Hay ME (eds) *Marine Community Ecology* Sinauer Associates, Inc. , Sunderland, Massachusetts

- VanBlaricom GR (1988) Effects of foraging by sea otters on mussel-dominated intertidal communities. In: VanBlaricom GR, Estes JA (eds) The community ecology of sea otters. Springer-Verlag, Berlin
- Vermeer K (1983) Diet of the Harlequin Duck in the Strait of Georgia, British Columbia. *The Murrelet* 64:54-57
- Waldeck P, Larsson K (2013) Effects of winter water temperature on mass loss in Baltic blue mussels: Implications for foraging sea ducks. *J Exp Mar Biol Ecol* 444:24-30
- Webster JD (1941) Feeding habits of the Black Oyster-catcher. *Condor*:175-180
- Weingartner TJ (2005) Physical and geological oceanography: coastal boundaries and coastal and ocean circulation. In: Mundy PR (ed) *The Gulf of Alaska, Biology and Oceanography*. Alaska Sea Grant Program, University of Alaska, Fairbanks, AK
- Weingartner TJ, Danielson SL, Royer TC (2005) Freshwater variability and predictability in the Alaska Coastal Current. *Deep Sea Research Part II: Topical Studies in Oceanography* 52:169-191
- Widdows J (1991) Physiological ecology of mussel larvae. *Aquaculture* 94:147-163
- Witman JD, Genovese SJ, Bruno JF, McLaughlin JW, Pavlin BI (2003) Massive prey recruitment and the control of rocky subtidal communities on large spatial scales. *Ecological Monographs* 73:441-462
- Wootton JT, Forester JD (2013) Complex Population Dynamics in Mussels Arising from Density-Linked Stochasticity. *PLoS One* 8
- Yaroslavtseva LM, Sergeeva EP (2006) Adaptivity of the bivalve *Mytilus trossulus* larvae to short-and long-term changes in water temperature and salinity. *Russian Journal of Marine Biology* 32:82-87

Chapter 5 LINGERING OIL MONITORING

INTRODUCTION TO LINGERING OIL MONITORING

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Introduction

Gulf Watch Alaska is funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC), and includes continued examination of effects of the oil spill, as well as monitoring of ecosystem variation that influences species and services injured by the spill. A major issue associated with prolonged recovery of some species is that of “lingering oil”, i.e., *Exxon Valdez* oil persisting in intertidal sediments with subsequent exposure and effects on nearshore wildlife. The Lingering Oil Component of Gulf Watch Alaska is designed to monitor the occurrence and state of lingering *Exxon Valdez* oil, and to evaluate direct effects on vulnerable wildlife species.

Background

Extent and Timeline of Diminishment of Lingering Oil

In March 1989, the T/V *Exxon Valdez* ran aground on Bligh Reef in eastern Prince William Sound (PWS), spilling an estimated 42 million liters of crude oil (Wolfe et al. 1994). In the days and weeks after the incident, spilled oil moved south and west through PWS and then into the Gulf of Alaska (Figure 5-1; Galt et al. 1991). Roughly 40% of the spilled oil landed on beaches within PWS (Galt et al. 1991), affecting at least 783 km of shoreline (Short et al. 2004). The extent and degree of oiling on shorelines decreased rapidly over the first few years after the spill, and it was assumed that remaining oil would be reduced to negligible amounts soon thereafter (Neff et al. 1995). However, observations up to 8 years after the spill indicated that oil remained in intertidal sediments of some beaches (Hayes and Michel 1999) leading to concerns that lingering oil could continue to have harmful effects on fish and wildlife populations, and the nearshore ecosystem.

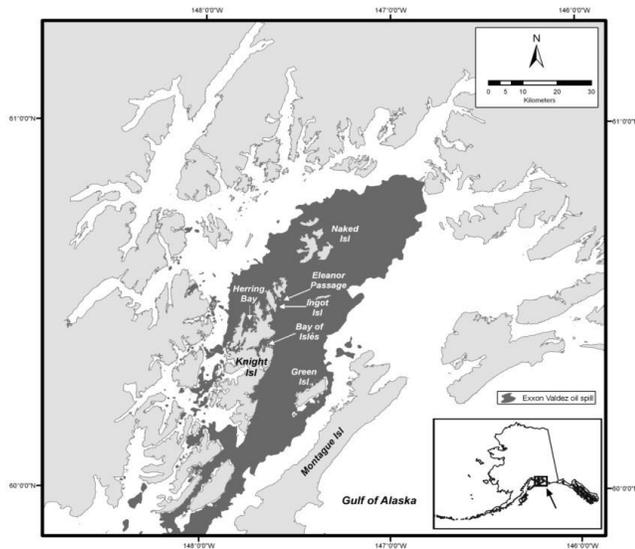


Figure 5-1. Area of Prince William Sound, Alaska affected by oil from the 1989 Exxon Valdez spill (Monson et al. 2011).

Prompted by concerns about lingering *Exxon Valdez* oil, a study was initiated in 2001 (12 years after the spill) to evaluate the amount and distribution of lingering oil in PWS. Short et al. (2004) found that both surface residues and subsurface oil persisted on some beaches, including the majority of beaches that were classified as heavily or moderately oiled within 4 years of the spill. Surface deposits were highly weathered and largely transformed into asphalt-like material, which was considered to have low toxicity and low bioavailability and pose minimal threats to fish and wildlife. However, subsurface oil was liquid and much less weathered than surface residues (Hayes and Michel 1999), leading to concerns that the subsurface oil might be both bioavailable and toxic. Short et al. (2004) estimated that the areal extent of subsurface oil in 2001 was 7.8 ha and the mass of remaining oil was 55,600 kg. These were considered to be moderate underestimates, given several factors that would lead to a low bias (Short et al. 2006). For example, subsurface oil was found lower in the intertidal than anticipated, at elevations not sampled during the 2001 effort; this may have led to an underestimate by roughly 30% (Short et al. 2006). Despite uncertainty about the exact amount of lingering oil, all estimates were well under 1% of the amount thought to have originally stranded on PWS beaches. However, the mass and volume remaining and the toxic potential of subsurface oil elicited continued concerns about effects of lingering oil on wildlife populations.

Subsurface oil presumably has been declining in occurrence and extent over time, through disturbance of sediments associated with storm events, foraging by intertidal animals, including sea otters, and other releasing, weathering, and degrading processes. The rate at which attenuation occurs is unknown and presumably becomes progressively lower over time (Short et al. 2004, 2007, Integral 2006), with oil persisting longest in areas that are least susceptible to depletion processes (Short et al. 2007, Michel et al. 2010). As of the time of this report, it is known that some oil remains within sediments of some beaches of PWS (Li and Boufadel 2010, Xia and Boufadel 2011) (authors' personal observations), and recent

efforts have estimated the distribution of lingering oil patches (Michel et al. 2010). However, the current amount of lingering oil, and thus the degree to which it has declined since estimates were made using data from 2001 and 2003 (Short et al. 2004b), are not known. We note that residual *Exxon Valdez* oil also has persisted and remains in some areas outside of PWS (Irvine et al. 2006, 2014, Short et al. 2007); again, the amount of that oil is uncertain.

Exposure and Effects of Lingering Oil on Wildlife

For lingering oil to have effects on wildlife individuals and populations, animals must be exposed to that oil at levels that have meaningful biological consequences. This requires evaluation of the timeline and degree of exposure, as well as the timeline and degree of effects, which cannot be assumed to be the same and which vary considerably among species (see Esler et al., this report).

Following the *Exxon Valdez* oil spill, numerous studies indicated that wildlife continued to be exposed to oil well beyond the first weeks and months after the spill. Many of the studies of oil exposure were based on indicators of cytochrome P4501A (CYP1A) induction, which is elevated in animals when they are exposed to one of a limited number of compounds, including polycyclic aromatic hydrocarbons found in crude oil. Differences in indicators of oil exposure animals living in oiled and unoiled areas of PWS were largest and most persistent for animals in intertidal habitats, particularly those that consume benthic invertebrates that live on or in the sediment, such as harlequin ducks (Esler et al. 2010).

To assess potential for oil exposure in sea otters, a recent study (Bodkin et al. 2012) estimated the average number of times a sea otter would encounter oil annually at heavily oiled northern Knight Island, based on 19 sea otters with abdominally-implanted time and depth recorders. Bodkin et al. (2012) found that while 82 percent of the more than a million foraging dives were subtidal (not at risk for encountering lingering oil), all individuals foraged in intertidal zones at least some of the time. Each otter averaged between 8 and 91 intertidal foraging dives per day. From these data, Bodkin et al. (2012) estimated that sea otters would encounter subsurface lingering oil an average of 10 times each year, ranging from 2 to 24 times, depending on individual foraging routines and based on oil distributions in the early 2000s.

In summary, the body of evidence suggests that many intertidally-foraging vertebrates were exposed to lingering *Exxon Valdez* oil for years to decades post-spill. The data indicate improvement in conditions over time, with varying timelines of exposure among species (see Esler et al., this report). These findings not only indicate the expected pattern of declining exposure over time, they also support the conclusion that elevated levels observed earlier were related to exposure to *Exxon Valdez* oil when it was more abundant, rather than other contaminants.

As a result of evidence that sea otter and harlequin ducks were more vulnerable to effects of the *Exxon Valdez* oil spill than other wildlife (see Esler et al., this report), detailed examinations of population recovery have been conducted for these two species. Studies conducted prior to initiation of Gulf Watch Alaska indicated direct effects of exposure to lingering oil on both sea otters and harlequin ducks.

Recent Activities within Gulf Watch Alaska

The Lingering Oil component of Gulf Watch Alaska has focused on continued evaluation of exposure and population status of sea otters and harlequin ducks, the two species with strongest evidence of continued, direct effects of lingering oil. For harlequin ducks, these efforts have included continued monitoring of

CYP1A induction to evaluate exposure to lingering oil. For sea otters, activities include collection of carcasses to document age class distributions of dying otters as an indicator of mortality patterns and aerial surveys to evaluate changes to abundance and distribution.

Recent evidence indicates both cessation of continued exposure to lingering *Exxon Valdez* oil, as well as recovery of sea otter and harlequin duck populations (see Esler et al., this report). As the signal from the oil spill diminishes, the value of the data collected during Gulf Watch Alaska becomes more relevant for understanding natural variation and interactions within the nearshore ecosystem.

Considerations for Future Directions

Although there is no evidence of continuing effects on wildlife, lingering *Exxon Valdez* oil remains within the beaches of PWS and elsewhere in the Gulf of Alaska. The amount of lingering oil is small relative to the amount that originally stranded (Short et al. 2004) and presumably has diminished since the last quantitative estimate was conducted in 2001 and 2003. A lingering oil monitoring survey will be conducted in PWS during the summer of 2015 at 10-12 sites known to have persistent subsurface *Exxon Valdez* oil. Continued monitoring of these sites will allow us to quantify how much oil remains and assess the oil's weathering state through time. Because the rate of change is expected to be slow, intermittent evaluation (e.g., once every 5 years) is likely adequate.

The body of work supported by the EVOSTC over a 25-year period, leading up to and including that of Gulf Watch Alaska, has led to an unprecedented understanding of the mechanisms and duration of effects on wildlife following a catastrophic oil spill. As presented by Esler et al. (this report), latest findings indicate that direct effects of lingering *Exxon Valdez* oil on wildlife in PWS are no longer detectable. Given the most recent findings, additional monitoring related to wildlife effects of lingering oil is unlikely to provide new information.

References

- Bodkin, J. L., B. Ballachey, H. Coletti, G. Esslinger, K. Kloecker, S. Rice, J. Reed, and D. Monson. 2012. Long-term effects of the “*Exxon Valdez*” oil spill: sea otter foraging in the intertidal as a pathway of exposure to lingering oil. *Marine Ecology Progress Series* 446:273-287.
- Esler, D., K. A. Trust, B. E. Ballachey, S. A. Iverson, T. L. Lewis, D. J. Rizzolo, D. M. Mulcahy, A. K. Miles, B. R. Woodin, J. J. Stegeman, J. D. Henderson, and B. W. Wilson. 2010. Cytochrome P4501A biomarker indication of oil exposure in harlequin ducks up to 20 years after the “*Exxon Valdez*” oil spill. *Environmental Toxicology and Chemistry* 29(5):1138-45.
- Galt, J. A., W. J. Lehr, and D. L. Payton. 1991. Fate and transport of the “*Exxon Valdez*” oil spill. Part 4. *Environmental Science and Technology* 25(2):202-209.
- Hayes, M. O., and J. Michel. 1999. Factors determining the long-term persistence of “*Exxon Valdez*” oil in gravel beaches. *Marine Pollution Bulletin* 38(2):92-101.
- Integral, I. 2006. Project 060783 Final Report: Information Synthesis and Recovery Recommendations for Resources and Services Injured by EVOS. Anchorage, AK.

- Irvine, G. V., D. H. Mann, M. G. Carls, L. G. Holland, C. Reddy, R. K. Nelson, and C. Aepli. 2014. Lingering Oil on Boulder-Armored Beaches in the Gulf of Alaska 23 Years after the “*Exxon Valdez*” Oil Spill, “*Exxon Valdez*” Oil Spill Restoration Project Final Report (Restoration Project 11100112), U.S. Geological Survey, Alaska Science Center. Anchorage, Alaska.
- Irvine, G. V., D. H. Mann, and J. W. Short. 2006. Persistence of 10-year old “*Exxon Valdez*” oil on Gulf of Alaska beaches: the importance of boulder-armoring. *Marine pollution bulletin* 52(9):1011–22.
- Li, H., and M. C. Boufadel. 2010. Long-term persistence of oil from the “*Exxon Valdez*” spill in two-layer beaches. *Nature Geoscience* 3(2):96–99.
- Michel, J., Z. Nixon, M. O. Hayes, J. W. Short, G. V. Irvine, D. V. Betenbaugh, C. Boring, and D. H. Mann. 2010. Distribution of Subsurface Oil from the *Exxon Valdez* Oil Spill, *Exxon Valdez* Oil Spill Restoration Project Final Report (Project 070801). National Oceanic and Atmospheric Administration, Juneau, AK.
- Monson, D. H., D. F. Doak, B. E. Ballachey, and J. L. Bodkin. 2011. Could residual oil from the Exxon Valdez spill create a long-term population “sink” for sea otters in Alaska? *Ecological Applications* 21(8):2917–2932.
- Neff, J. M., E. H. Owens, S. W. Stoker, and D. M. McCormick. 1995. Shoreline oiling conditions in Prince William Sound following the “*Exxon Valdez*” oil spill. In “*Exxon Valdez*” Oil Spill: Fate and Effects in Alaskan Waters:312–346.
- Short, J. W., G. V. Irvine, D. H. Mann, J. M. Maselko, J. J. Pella, M. R. Lindeberg, J. R. Payne, W. B. Driskell, and Rice. 2007. Slightly Weathered *Exxon Valdez* Oil Persists in Gulf of Alaska Beach Sediments after 16 Years. *Environmental Science and Technology* 41:1245–1250.
- Short, J. W., M. R. Lindeberg, P. M. Harris, J. M. Maselko, J. J. Pella, and S. D. Rice. 2004. Estimate of oil persisting on the beaches of Prince William Sound 12 years after the “*Exxon Valdez*” oil spill. *Environmental science & technology* 38(1):19–25.
- Short, J. W., J. M. Maselko, M. R. Lindeberg, P. M. Harris, and S. D. Rice. 2006. Vertical distribution and probability of encountering intertidal “*Exxon Valdez*” oil on shorelines of three embayments within Prince William Sound, Alaska. *Environmental Science and Technology* 40(12):3723–9.
- Wolfe, D. A., M. J. Hameedi, J. A. Galt, G. Watabayashi, J. Short, C. O’Claire, S. Rice, J. Michel, J. R. Payne, J. Braddock, S. Hanna, and D. Sale. 1994. The fate of the oil spilled from the “*Exxon Valdez*”. *Environmental Science and Technology* 28(13):560A–8A.
- Xia, Y., and M. C. Boufadel. 2011. Beach geomorphic factors for the persistence of subsurface oil from the “*Exxon Valdez*” spill in Alaska. *Environmental Monitoring and Assessment* 183(1-4):5–21.

TIMELINES AND MECHANISMS OF WILDLIFE POPULATION RECOVERY FOLLOWING THE *EXXON VALDEZ* OIL SPILL

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Background and objectives

In March 1989, the *T/V Exxon Valdez* ran aground in Prince William Sound (PWS), Alaska and spilled an estimated 42 million liters of crude oil (Wolfe et al. 1994). This oil subsequently spread over more than 26,000 km² of water surface in PWS and the Gulf of Alaska and landed on more than 1000 km of shoreline (Spies et al. 1996, Short et al. 2004; see Fig. 1 in Esler et al., this report). Initial consequences for wildlife were immediate and obvious. Mortalities due to oil in the weeks following the spill were estimated to be in the hundreds of thousands of marine birds (Piatt et al. 1990), several thousand sea otters (Garrott et al. 1993, Ballachey et al. 1994), significant proportions of resident (33%) and transient (41%) pods of killer whales (Matkin et al. 2008), and varying numbers of a wide assortment of other wildlife species. These levels of mortality are consistent with expectations, given the amount of oil spilled, the size of the oil-affected area, the abundance of wildlife in the area, and the known toxic and thermoregulatory consequences of exposure to oil, particularly in cold-water environments.

Other effects of oil spills on wildlife, including chronic or indirect effects, were not fully understood, recognized, or anticipated at the time of the *Exxon Valdez* oil spill (EVOS) (Peterson et al. 2003, Rice 2009). Thanks in large part to settlement funds managed by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC), including that for Gulf Watch Alaska in recent years, a considerable body of research has addressed wildlife recovery from the spill. This has allowed for an unprecedented and thorough understanding of the timelines and mechanisms of population recovery following catastrophic spills. In this document, we review the timelines and processes of recovery of wildlife from the EVOS. We also consider factors that result in variation in recovery times across species, and present recent data for two species that showed protracted recovery related to exposure from lingering oil, the sea otter (*Enhydra lutris*) and harlequin duck (*Histrionicus histrionicus*).

What is “recovery”?

The body of literature addressing wildlife recovery following the EVOS includes some controversy about occurrence, degree, and source of effects on individuals and populations (e.g., Irons et al. 2000, Wiens et al. 2001). Some of that controversy stems from varying definitions of recovery. Therefore, for the purposes of this document, we note explicitly that we are subscribing to the EVOSTC definitions of recovery (<http://www.evostc.state.ak.us/>). These definition can vary by species but generally require return to conditions that would have been present had the spill not occurred (acknowledging the difficulties associated with determining that) and also abatement of exposure of animals to hydrocarbons lingering since the spill (see Esler et al., this report).

Varying mechanisms of effect

The thorough considerations of injury and recovery of marine ecosystems following the EVOS have contributed to a growing understanding of the variety of ways in which pollution can affect wildlife populations, both acute and chronic, and direct and indirect (Peterson et al. 2003). Wildlife mortality has been documented in association with many large oil spills (e.g., Flint et al. 1999, Goldsworthy et al. 2000,

Munilla et al. 2011). Much of this mortality occurred in the days and weeks following these events, when freshly spilled oil is readily encountered by wildlife; we term this time period to be the “acute” phase of effects on wildlife. As indicated above, acute mortality of many wildlife species was observed after the EVOS. It is now recognized that acute mortality is only one of the ways in which oil spills can affect wildlife (Peterson et al. 2003). Effects expressed beyond the acute phase, which we refer to as “chronic” effects, can extend for months, years, or decades and, in some cases, may exceed the magnitude of acute mortalities (Iverson and Esler 2010, Monson et al. 2011). Chronic oil spill effects were not generally considered at the time of the *Exxon Valdez* event, but have been subsequently (Peterson et al. 2003).

Chronic effects of oil spills on wildlife can be manifested in a number of ways, including direct and delayed toxic effects, demographic lags, and indirect effects, which we review here.

Direct chronic effects occur due to toxic or thermoregulatory effects of exposure to oil after the acute phase. In the case of the EVOS, oil has persisted in the environment since the time of the spill (Short et al. 2004, 2006, Michel et al. 2010, Irvine et al. 2014). This “lingering oil” represents a tiny fraction of the spilled oil, but occurs in a largely unweathered state in subsurface sediments of beaches with certain physical characteristics that sequester the oil (Michel et al. 2010; see Esler et al., this report). Lingering oil presumably declines in occurrence, extent, and toxicity over time; however, studies indicate that several wildlife species were exposed to lingering oil over years to decades (see below). Although exposure to lingering oil does not necessarily imply subsequent effects (Lee and Anderson 2005), it does allow for the possibility of direct chronic effects; in the case of the EVOS, evidence for some species indicated that these direct effects occurred (see below).

Delayed toxic effects are consequences of oil exposure that are not expressed until months, years, or decades after that exposure. Oil ingestion can cause immune suppression, damage to genetic material, damage to a suite of organ systems, and oxidative stress. The effects of these might not be fatal to the affected animal until long after the exposure has ceased, via tumor formation, organ failure, or reductions in disease resistance (e.g., Miles et al. 2012). Also, toxic effects may act synergistically with natural stressors, with the combined cumulative effects leading to mortality (Holmes et al. 1979). Premature death as a result of delayed toxic effects could have significant effects on wildlife population dynamics (Monson et al. 2011).

Chronic effects also result from demographic lags, i.e., the time it takes for populations to return to conditions that would have existed in the absence of the spill, after direct oil effects have ceased. In other words, there are constraints on how fast populations can increase in abundance and these can delay recovery. The importance of demographic lags depends on a number of species-specific factors, including maximum reproductive potential, rates of dispersal, population structure, and other factors influencing density dependence. However, it is clear that immediate recovery did not occur following cessation of direct survival effects of the EVOS for a number of taxa and demographic lags were undoubtedly involved to some degree (Matkin et al. 2008, Iverson and Esler 2010, Monson et al. 2011).

Finally, chronic effects can result from **indirect effects** that can take a number of forms. Generally, indirect effects refer to oil spill-induced changes to the environment that, in turn, have deleterious consequences for wildlife. These could result from changes in prey availability or predator abundance, for example, or from other cascading effects that occur upon disruption of complex food webs (Peterson et al. 2003). Indirect effects related to EVOS-induced changes to prey availability have been implicated as a

contributing factor constraining recovery for some taxa (Golet et al. 2002) but rejected for others (Dean et al. 2002, Esler et al. 2002).

Review of recovery timelines across wildlife species

In this section, we introduce a suite of species that exemplify variation in injury and recovery timelines (Figure 5-2) and in the following section discuss varying mechanisms and degrees of effects of the oil spill. Different wildlife species have different vulnerabilities to the suite of potential effects of oil spills described above. Those vulnerabilities are influenced by life history characteristics, such as generation times, reproductive potential and natural survival rates, along with natural history characteristics, such as habitat use, diet, and foraging behavior. Given the diversity of wildlife species occurring in marine habitats of the northern Gulf of Alaska, it is not surprising that effects of the EVOS varied. In this section, we consider a suite of species that exemplify the varying mechanisms and degrees of effects of the oil spill, with resulting variation in injury and recovery timelines (Figure 5-2).

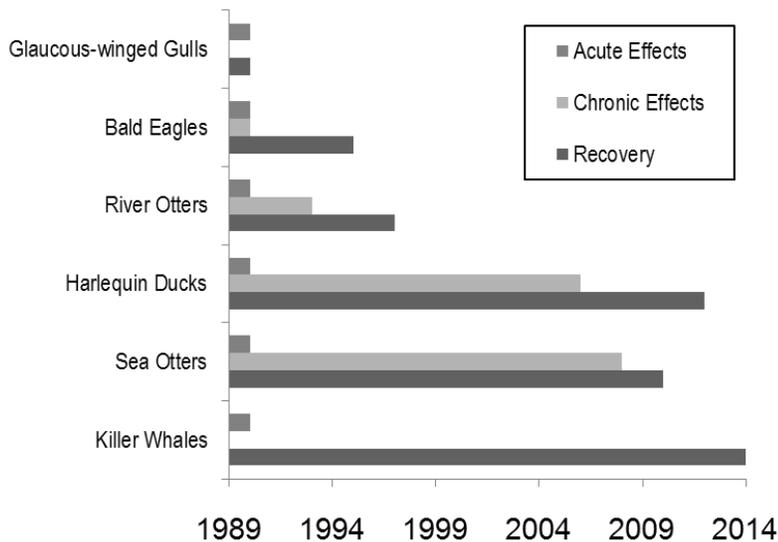


Figure 5-2. Examples of timelines of injury and recovery of selected species following the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska.

Glaucous-winged gulls (*Larus glaucescens*) are representative of species for which relatively small numbers of acute mortalities were detected (Piatt et al. 1990). Densities may have been depressed during the year of the spill, but no chronic injury or lack of recovery was evident (Day et al. 1997, Irons et al. 2000, Cushing et al. 2012).

Bald eagles (*Haliaeetus leucocephalus*) experienced roughly 5% acute mortality in PWS and significantly reduced reproductive performance in oiled areas during 1989, the year of the spill (Bowman et al. 1997). However, no differences in survival or reproduction were observed in subsequent years (Bowman et al. 1995), and bald eagles were considered to have recovered by 1995 based on return to pre-spill numbers.

River otters (*Lontra canadensis*) in oiled areas expressed values for a variety of biomarkers indicative of poor health during the years immediately following the EVOS (1989 – 1992), presumably as a result of direct chronic exposure to oil (Bowyer et al. 2003). Habitat use, diet, and body mass also differed between river otters living in oiled and unoiled areas during that period. By the mid-1990s, many of these attributes had improved, and Bowyer et al. (2003) concluded that river otters had recovered by 1997.

Harlequin ducks have been intensively studied since the spill. Several lines of evidence indicate direct chronic injury and protracted recovery. Densities were lower in oiled areas than expected through 1997, after accounting for habitat attributes (Esler et al. 2000a). Also, adult female survival in oiled areas was depressed up to a decade following the spill (Esler et al. 2000b), coincident with biomarker evidence of exposure to lingering oil (Trust et al. 2000). By 2003, survival rates had returned to normal, despite continued oil exposure (Esler and Iverson 2010). Demographic data were assembled in a population model, and the best estimate of time until full recovery was 24 years post-spill, or 2013, due in part to demographic lags (Iverson and Esler 2010). However, biomarker data indicated that harlequin ducks continued to be exposed to oil through at least 2009 (Esler et al. 2010). Recent findings indicate lack of exposure to oil by 2013 (see below) and hence recovery from effects of the spill.

Sea otters are another species for which exposure to lingering oil led to direct chronic effects. Population models were developed to determine the timeline and spatial extent of mortalities related to chronic effects of the *Exxon Valdez* spill, using age distributions of living and dead otters and spatially-explicit population trend data (Monson et al. 2000, 2011). These models indicated that mortality rates were higher in areas affected by lingering oil until at least 2005, at which point survival effects began to dissipate. These findings are consistent with sea otter survey data since the spill, which showed depressed numbers in heavily oiled areas through 2009. The most recent findings indicate mortality patterns and abundance have returned to pre-spill conditions (see below).

Killer whales (*Orcinus orca*) suffered acute mortalities in both a resident and transient pod that occur in PWS (Matkin et al. 2008, Matkin et al., this report). Neither of these pods has recovered to pre-spill numbers, although it is unlikely that exposure to lingering oil is leading to chronic direct effects. Killer whale recovery is constrained by demographic factors associated with life history characteristics and small population size. Timeline to recovery for this species is unknown, and it is possible that the transient pod will never recover (Matkin et al., this report).

Factors related to recovery timelines

As indicated above, mechanisms leading to oil spill injury and timelines to population recovery vary widely among wildlife species. In the acute phase of oil spills, wildlife that spend much of their time on the ocean surface are particularly vulnerable to direct spill effects (Piatt et al. 1990, Goldsworthy et al. 2000), as that is where much of the oil occurs. For example, killer whales were observed surfacing in oil slicks (Matkin et al. 2008). In the chronic phase, much of the bioavailable oil is found in intertidal habitats, so wildlife that use those habitats are more likely to be exposed to oil and therefore to be subject to direct chronic effects of exposure. In the case of the *Exxon Valdez* spill, wildlife utilizing intertidal habitats showed chronic exposure, chronic direct effects of oil, or both. These included river otters (Bowyer et al. 2003), harlequin ducks (Esler et al. 2002, 2010), and sea otters (Bodkin et al. 2002, Dean et al. 2002, Monson et al. 2011, Bodkin et al. 2012), mentioned above, as well as pigeon guillemots

(*Cephus columba*; Golet et al. 2002), black oystercatchers (*Haematopus bachmani*; Andres 1999), and Barrow's goldeneyes (*Bucephala islandica*; Esler et al. 2011).

In addition to habitat use, diet also can influence vulnerability to oil exposure during the chronic phase of oil spills, and thus likelihood of injury and delayed population recovery. In the case of the *Exxon Valdez* spill, wildlife that consume benthic invertebrates were more likely to be exposed to oil and subject to chronic direct effects (Peterson and Holland-Bartels 2002). There may be multiple reasons for this; first, wildlife consuming benthic invertebrates are foraging on, and in some cases digging into, sediments that may contain lingering oil (Bodkin et al. 2012). Second, invertebrate prey, particularly filter feeders, may accumulate hydrocarbons (Fukuyama et al. 2000, Thomas et al. 2007) that, once consumed, may lead to detrimental effects on the wildlife consumers. Species consuming vertebrate prey (e.g., fish), such as river otters (see above), may be less vulnerable to prey-mediated exposure, as vertebrate prey are not likely to accumulate hydrocarbons because they possess physiologic mechanisms capable of metabolizing and eliminating hydrocarbons.

Wildlife species also vary in their thermal or metabolic sensitivity to oil exposure. For example, during the acute phase of the EVOS, sea otters were considered to be more vulnerable than other marine mammals to effects of external oiling, due to their reliance on their fur for insulation and lack of a substantial blubber layer (Ballachey et al. 1994). Birds in cold water environments are known to be highly susceptible to hypothermia when their insulation is compromised due to feather oiling (Jenssen and Ekker 1991). External oiling also is possible during the chronic phase of oil spills, if oil sequestered in the environment is released through disturbance of sediments by storms or foraging animals (Bodkin et al. 2012). Wildlife species also may be metabolically sensitive to effects of oil exposure due to naturally high metabolic rates (e.g., sea otters, Bodkin et al. 2002) or little scope to accommodate additional energetic costs due to oil exposure (e.g. harlequin ducks, Esler et al. 2002).

Life history characteristics also influence recovery times of wildlife to perturbations, including those of oil spills. Species with high reproductive rates and short generation times will recover more quickly than those with life histories oriented towards long life spans. As the extreme example in the case of the EVOS, recovery of the AB resident pod of killer whales has still not occurred over 25 years after the initial, acute mortality (Matkin et al. 2008, Matkin et al., this report).

Updates on recovery status of sea otters and harlequin ducks

As indicated above, sea otters and harlequin ducks were among the species with the most protracted recovery times following the EVOS, with lingering oil implicated as the primary constraint to full recovery. This resulted from their combination of characteristics that led to increased vulnerability to spill effects, including use of intertidal habitats where oil persisted, consumption of benthic invertebrates, and life histories constraining population growth potential (Peterson and Holland-Bartels 2002). For both species, lack of recovery was linked to direct chronic effects of exposure to residual oil and, in 2010, the EVOSTC considered sea otters and harlequin ducks to be recovering but not fully recovered. Recent data, collected as part of Gulf Watch Alaska, provide new insights on the recovery timeline of sea otters and harlequin ducks, and the EVOSTC declared both species recovered in 2014 (*Exxon Valdez* Oil Spill Trustee Council 2014).

Sea otter abundance

Recent sea otter data are presented and interpreted by Ballachey et al. 2014; we briefly summarize key findings here. Since 1993, sea otter abundance has been quantified based on aerial survey methods (Bodkin and Udevitz 1999) throughout western PWS, including the northern Knight Island archipelago, where heavy oiling resulting in strong acute and chronic effects on otters and, thus, where recovery was most delayed. Pre-spill numbers at northern Knight Island were estimated as the number of living animals observed in, as well as the number of carcasses recovered from, the northern Knight Island survey area (Dean et al. 2000).

Sea otter abundance in western PWS has been increasing since shortly after the oil spill (Ballachey et al. 2014), likely reflecting recovery from mortalities as a result of the oil spill; however, comparable estimates from before the spill are not available at this spatial scale. At northern Knight Island, sea otter abundance was below estimated pre-spill abundance through 2009, 20 years after the *Exxon Valdez* spill (Figure 5-3). However, in the 3 most recent years of surveys (2011, 2012, and 2013), abundance was similar to the pre-spill estimate (Figure 5-3). Given that northern Knight Island likely represents a “worst-case scenario” in terms of sea otter recovery, these recent data are an encouraging sign that sea otter status in PWS met the recovery criteria set by the EVOSTC, and in 2014 sea otters were declared recovered (*Exxon Valdez* Oil Spill Trustee Council 2014).

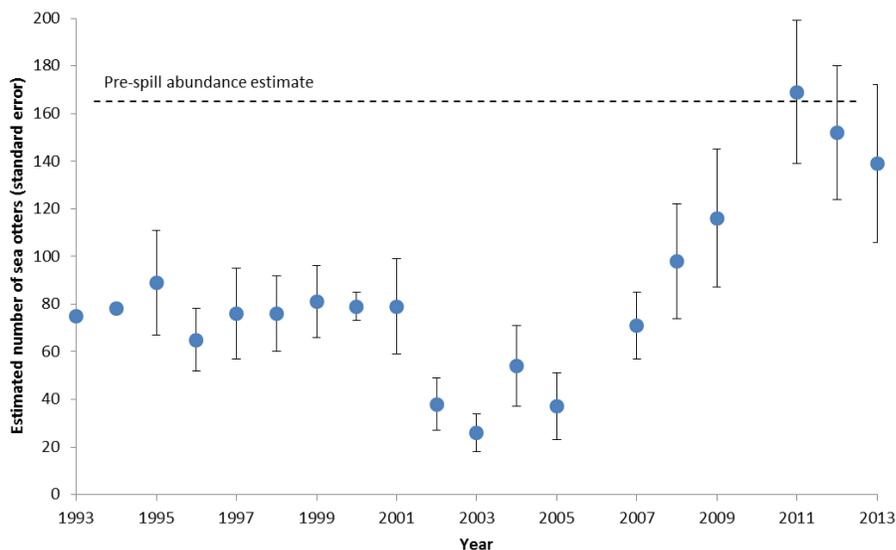


Figure 5-3. Estimated numbers of sea otters (\pm standard error) at heavily oiled northern Knight Island, Prince William Sound, Alaska, 1993–2013 relative to a pre-spill abundance estimate (from Ballachey et al. 2014).

Sea otter age distribution at death

The age distribution of sea otter carcasses recovered from beaches in western PWS each spring has proven to be an important gauge of population status (Monson et al. 2000, 2011). Discovered carcasses

are assumed to be representative of mortality patterns in the population. Teeth are extracted from carcasses to assign age, based on cementum layers.

Under normal conditions, mortalities in sea otters, like most other long-lived mammals, are concentrated in the youngest (0-1 years) and oldest (> 8 years) age classes. This pattern is evident in data from western PWS collected prior to the EVOS (Figure 5-4). However, during the year of the spill (1989) and the subsequent 20 years, a different pattern of mortality was evident, with higher proportions of prime-age (2-8 years) otters dying. This difference was interpreted as evidence of elevated mortality related to effects of oil exposure (Monson et al. 2000, 2011). However, in recent years (2010 to 2013), mortality patterns were similar to those expected under normal conditions and observed pre-spill (Figure 5-4). These data suggest that between 20 and 25 years after the spill direct chronic or delayed toxic effects of the EVOS were no longer causing sea otter mortality.

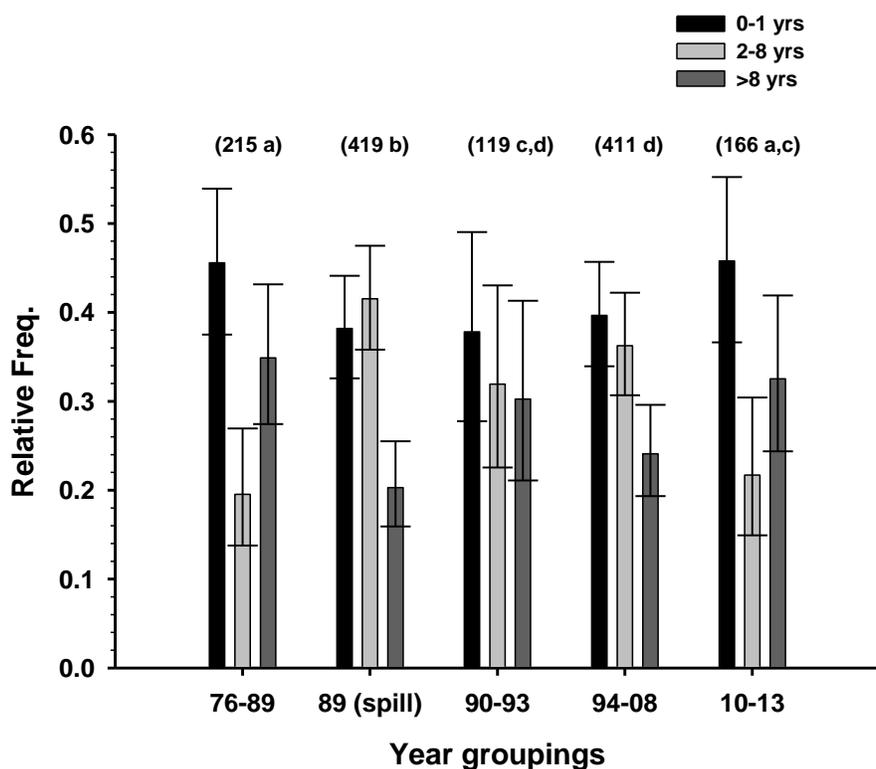


Figure 5-4. Relative age distributions of sea otter carcasses collected on western Prince William Sound beaches from 1976 to 2013. Total numbers of carcasses collected are in parentheses above each grouping and distributions with the same letter do not differ significantly from each other (from Ballachey et al. 2014).

Harlequin duck exposure to oil

Exposure to *Exxon Valdez* oil in harlequin ducks has been evaluated since 1998, through use of indicators of induction of members of the cytochrome P450 1 gene subfamily (CYP1A). Vertebrate CYP1A genes are induced by exposure to hydrocarbons, including those found in crude oil, as well as a limited number of other compounds that do not occur in high concentrations in PWS (Ricca et al. 2010). This is a proven, sensitive, and specific biomarker of oil exposure. CYP1A is assayed via 7-ethoxyresorufin-O-deethylase (EROD) activity in liver biopsies surgically taken from captured harlequin ducks, and compared between oiled and unoiled areas of PWS. In previous work (Trust et al. 2000, Esler et al. 2010), EROD activity was elevated in harlequin ducks from oiled areas through 2009 (Figure 5-5), which was interpreted as evidence of continued exposure to *Exxon Valdez* oil.

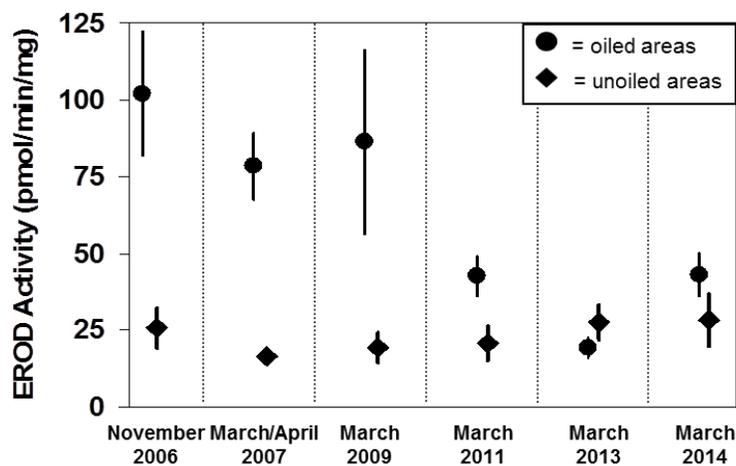


Figure 5-5. Average (\pm SE) hepatic 7-ethoxyresorufin-O-deethylase (EROD) activity (pmol/min/mg protein) of harlequin ducks captured in Prince William Sound, Alaska in March 2013 and 2014 ($n = 50$ each year), contrasted with results from previous years (Esler et al. 2010)

Recent data, including those collected as part of Gulf Watch Alaska, indicate reduction of exposure to lingering *Exxon Valdez* oil. In 2011, indices of CYP1A activity of harlequin ducks from oiled areas were lower than in previous years, although still statistically different from those in unoiled areas (Figure 5-5). In 2013 and 2014, average EROD activity did not differ between harlequin ducks from oiled and unoiled areas of PWS (Fig. 4). We interpret these data to indicate that exposure to lingering oil had largely ceased by 2013, 24 years after the EVOS.

Conclusions

The large amount of research on wildlife following the EVOS, including that conducted as part of Gulf Watch Alaska in recent years, led to unprecedented documentation of varying timelines of recovery and the opportunity to evaluate underlying constraints to recovery. This body of work resulted in some unexpected findings, including durations of recovery that were measured in decades for some species. Also, chronic exposure to oil persisting in intertidal sediments had stronger effects than anticipated,

including effects that outweighed acute mortality in some species. Recent data indicate that two species that had protracted recovery, sea otters and harlequin ducks, have recently met the recovery criteria of the EVOSTC, and both were declared recovered in 2014 (*Exxon Valdez* Oil Spill Trustee Council 2014). The results from this body of work have important implications for considerations of wildlife effects resulting from other oil spills, including the need for understanding chronic, demographic and ecosystem effects, to achieve a full accounting of the magnitude and timeline of wildlife losses. Also, the variety of constraints on recovery, which differ by species, offers generalizable insights for risk assessment and recovery planning.

References

- Andres, B.A. 1999. Effects of persistent shoreline oil on breeding success and chick growth in black oystercatchers. *Auk* 116(3):640-650.
- Ballachey, B.E., J.L. Bodkin, and A.R. DeGange, A.R. 1994. An overview of sea otter studies. Pages 47–59 in T. R. Loughlin, editor. *Marine mammals and the Exxon Valdez*. Academic Press, San Diego.
- Ballachey, B.E., D.H. Monson, G.G. Esslinger, K. Kloecker, J.L. Bodkin, L. Bowen, and A.K. Miles. 2014. 2013 update on sea otter studies to assess recovery from the 1989 *Exxon Valdez* oil spill, Prince William Sound, Alaska. U.S. Geological Survey Open-File Report 2014-1030:40.
- Bodkin J.L., B.E. Ballachey, H.A. Coletti, G.G. Esslinger, K.A. Kloecker, S.D. Rice, J.A. Reed, and D.H. Monson. 2012. Long-term effects of the *Exxon Valdez* oil spill: sea otter foraging in the intertidal as a pathway of exposure to lingering oil. *Marine Ecology Progress Series* 447:273-287.
- Bodkin J.L., B.E. Ballachey, T.A. Dean, A.K. Fukuyama, S.C. Jewett, L. McDonald, D.H. Monson, C.E. O'Clair, and G.R. VanBlaricom. 2002. Sea otter population status and the process of recovery from the 1989 *Exxon Valdez* oil spill. *Marine Ecology Progress Series* 241:237-253.
- Bodkin, J.L., and M.S. Udevitz. 1999. An aerial survey method to estimate sea otter abundance. *Marine Mammal Survey and Assessment Methods*:13-26.
- Bowman, T.D., P.F. Schempf, and J.A. Bernatowicz. 1995. Bald eagle survival and population-dynamics in Alaska after the *Exxon Valdez* oil spill. *Journal of Wildlife Management* 59(2):317-324.
- Bowman, T.D., P.F. Schempf, and J.I. Hodges. 1997. Bald eagle population in Prince William Sound after the *Exxon Valdez* oil spill. *Journal of Wildlife Management* 61(3):962-967.
- Bowyer R.T., G.M. Blundell, M. Ben-David, S.C. Jewett, T.A. Dean, and L.K. Duffy. 2003. Effects of the *Exxon Valdez* oil spill on river otters: Injury and recovery of a sentinel species. *Wildlife Monographs*(153):1-53.
- Cushing, D. A., A. McKnight, D. B. Irons, K. J. Kuletz, and S. Howlin. 2012. Prince William Sound marine bird surveys, synthesis and restoration. *Exxon Valdez Oil Spill Restoration Project Final Report* (Restoration Project 10100751), U. S. Fish and Wildlife Service, Anchorage, Alaska.
- Day, R.H., S.M. Murphy, J.A. Wiens, G.D. Hayward, E.J. Harner, and L.N. Smith. 1997. Effects of the *Exxon Valdez* oil spill on habitat use by birds in Prince William Sound, Alaska. *Ecological Applications* 7(2):593-613.

- Dean T.A., J.L. Bodkin, A.K. Fukuyama, S.C. Jewett, D.H. Monson, C.E. O'Clair, and G.R. VanBlaricom. 2002. Food limitation and the recovery of sea otters following the *Exxon Valdez* oil spill. *Marine Ecology Progress Series* 241:255-270.
- Dean, T.A., J.L. Bodkin, S.C. Jewett, D.H. Monson, and D. Jung. 2000. Changes in sea urchins and kelp following a reduction in sea otter density as a result of the *Exxon Valdez* oil spill. *Marine Ecology Progress Series* 199:281-291.
- Esler, D., B.E. Ballachey, K.A. Trust, S.A. Iverson, J.A. Reed, A.K. Miles, J.D. Henderson, B.W. Wilson, B.R. Woodin, J.R. Stegeman, M. McAdie, and D.M. Mulcahy.. 2011. Cytochrome P4501A biomarker indication of the timeline of chronic exposure of Barrow's goldeneyes to residual *Exxon Valdez* oil. *Marine Pollution Bulletin* 62(3):609-614.
- Esler, D., T. D. Bowman, T. A. Dean, C. E. O'Clair, S. C. Jewett, and L. L. McDonald. 2000a. Correlates of Harlequin Duck densities during winter in Prince William Sound, Alaska. *Condor* 102(4):920-926.
- Esler, D., T. D. Bowman, K. Trust, B. E. Ballachey, T. A. Dean, S. C. Jewett, and C. E. O'Clair. 2002. Harlequin duck population recovery following the *Exxon Valdez* oil spill: progress, process and constraints. *Marine Ecology Progress Series* 241:271-286.
- Esler, D., and S. A. Iverson. 2010. Female harlequin duck winter survival 11 to 14 Years after the *Exxon Valdez* oil spill. *Journal of Wildlife Management* 74(3):471-478.
- Esler, D., J. A. Schmutz, R. L. Jarvis, and D. M. Mulcahy. 2000b. Winter survival of adult female harlequin ducks in relation to history of contamination by the *Exxon Valdez* oil spill. *Journal of Wildlife Management* 64(3):839-847.
- Esler, D., K. A. Trust, B. E. Ballachey, S. A. Iverson, T. L. Lewis, D. J. Rizzolo, D. M. Mulcahy, A. K. Miles, B. R. Woodin, J. J. Stegeman, J. D. Henderson, and B. W. Wilson. 2010. Cytochrome P4501a biomarker indication of oil exposure in harlequin ducks up to 20 years after the *Exxon Valdez* oil spill. *Environmental Toxicology and Chemistry* 29(5):1138-1145.
- Exxon Valdez* Oil Spill Trustee Council. 2014. *Exxon Valdez* Oil Spill Restoration Plan. 2014 Update, Injured Resources and Services. Anchorage, AK: *Exxon Valdez* Oil Spill Trustee Council, 44p.
- Flint, P. L., A. C. Fowler, and R. F. Rockwell. 1999. Modeling bird mortality associated with the *M/V Citrus* oil spill off St. Paul Island, Alaska. *Ecological Modelling* 117(2-3):261-267.
- Fukuyama, A. K., G. Shigenaka, and R. Z. Hoff. 2000. Effects of residual *Exxon Valdez* oil on intertidal *Protothaca staminea*: Mortality, growth, and bioaccumulation of hydrocarbons in transplanted clams. *Marine Pollution Bulletin* 40(11):1042-1050.
- Garrott, R. A., L. L. Eberhardt, and D. M. Burn. 1993. Mortality of sea otters in Prince William Sound following the *Exxon Valdez* oil spill. *Marine Mammal Science* 9(4):343-359.
- Goldsworthy, S. D., R. P. Gales, M. Giese, and N. Brothers. 2000. Effects of the *Iron Baron* oil spill on little penguins (*Eudyptula minor*). I. Estimates of mortality. *Wildlife Research* 27(6):559-571.
- Golet, G. H., P.E. Seiser, A.D. McGuire, D.D. Roby, J.B. Fischer, K.J. Kuletz, D.B. Irons, T.A. Dean, S.C. Jewett, and S.H. Newman. 2002. Long-term direct and indirect effects of the *Exxon Valdez* oil spill on pigeon guillemots in Prince William Sound, Alaska. *Marine Ecology Progress Series* 241:287-304.

- Holmes, W.N., J. Gorsline, and J. Cronshaw. 1979. Effects of mild cold stress on the survival of seawater-adapted mallard ducks (*Anas platyrhynchos*) maintained on food contaminated with petroleum. *Environmental Research* 20:425–444.
- Irons, D. B., S. J. Kendall, W. P. Erickson, L. L. McDonald, and B. K. Lance. 2000. Nine years after the *Exxon Valdez* oil spill: Effects on marine bird populations in Prince William Sound, Alaska. *Condor* 102(4):723-737.
- Iverson, S. A., and D. Esler. 2010. Harlequin Duck population injury and recovery dynamics following the 1989 *Exxon Valdez* oil spill. *Ecological Applications* 20(7):1993-2006.
- Jenssen, B. M., and M. Ekker. 1991. Dose dependent effects of plumage-oiling on thermoregulation of common eiders *Somateria mollissima* residing in water. *Polar Research* 10(2):579-584.
- Lee, R. F., and J. W. Anderson. 2005. Significance of cytochrome P450 system responses and levels of bile fluorescent aromatic compounds in marine wildlife following oil spills. *Marine Pollution Bulletin* 50(7):705-723.
- Matkin, C. O., E. L. Saulifis, G. M. Ellis, P. Olesiuk, and S. D. Rice. 2008. Ongoing population-level impacts on killer whales *Orcinus orca* following the *Exxon Valdez* oil spill in Prince William Sound, Alaska. *Marine Ecology Progress Series* 356:269-281.
- Michel, J., Z. Nixon, M. O. Hayes, J. W. Short, G. V. Irvine, D. V. Betenbaugh, C. Boring, and D. H. Mann. 2010. Distribution of Subsurface Oil from the *Exxon Valdez* Oil Spill. *Exxon Valdez Oil Spill Restoration Project Final Report (Restoration Project 070801)*. National Oceanic and Atmospheric Administration, Juneau, Alaska.
- Miles, A. K., L. Bowen, B.E. Ballachey, J.L. Bodkin, M. Murray, J.L. Estes, R.A. Keister, and J.L. Stott. 2012. Variations of transcript profiles between sea otters *Enhydra lutris* from Prince William Sound, Alaska, and clinically normal reference otters. *Marine Ecology Progress Series* 451:201-212.
- Monson, D. H., D. F. Doak, B. E. Ballachey, and J. L. Bodkin. 2011. Could residual oil from the *Exxon Valdez* spill create a long-term population "sink" for sea otters in Alaska? *Ecological Applications* 21(8):2917-2932.
- Monson, D. H., D. F. Doak, B. E. Ballachey, A. Johnson, and J. L. Bodkin. 2000. Long-term impacts of the *Exxon Valdez* oil spill on sea otters, assessed through age-dependent mortality patterns. *Proceedings of the National Academy of Sciences* 97(12):6562-6567.
- Munilla, I., J.M., Arcos, D. Oro, D. Alvarez, P.M. Leyenda, and A. Velando. 2011. Mass mortality of seabirds in the aftermath of the *Prestige* oil spill. *Ecosphere* 2(7).
- Peterson, C.H., and L. Holland-Bartels. 2002. Chronic impacts of oil pollution in the sea: risks to vertebrate predators. *Marine Ecology Progress Series* 241:235-236.
- Peterson, C.H., S.D. Rice, J.W. Short, D. Esler, J.L. Bodkin, B.E. Ballachey, and D.B. Irons. 2003. Long-term ecosystem response to the *Exxon Valdez* oil spill. *Science* 302(5653):2082-2086.
- Piatt, J. F., C. J. Lensink, W. Butler, M. Kendziorek, and D. R. Nysewander. 1990. Immediate impact of the *Exxon Valdez* oil spill on marine birds. *Auk* 107(2):387-397.

- Ricca, M. A., A.K. Miles, B.E. Ballachey, J.L. Bodkin, D. Esler, and K.A. Trust. 2010. PCB exposure in sea otters and harlequin ducks in relation to history of contamination by the *Exxon Valdez* oil spill. *Marine Pollution Bulletin* 60(6):861-872.
- Rice, S. D. 2009. Persistence, toxicity, and long-term environmental impact of the *Exxon Valdez* oil spill. *University of St. Thomas Law Journal* 7(1):55-67
- Short, J. W., M.R. Lindeberg, P.M. Harris, J.M. Maselko, J.J. Pella, and S.D. Rice. 2004. Estimate of oil persisting on the beaches of Prince William Sound 12 years after the *Exxon Valdez* oil spill. *Environmental Science & Technology* 38(1):19-25.
- Short, J. W., J. M. Maselko, M. R. Lindeberg, P. M. Harris, and S. D. Rice. 2006. Vertical distribution and probability of encountering intertidal *Exxon Valdez* oil on shorelines of three embayments within Prince William Sound, Alaska. *Environmental Science & Technology* 40(12):3723-3729.
- Spies, R. B., S. D. Rice, D. A. Wolfe, and B. A. Wright. 1996. The effects of the *Exxon Valdez* oil spill on the Alaskan coastal environment. Pages 1-16 in *Proceedings of the Exxon Valdez Oil Spill Symposium*, volume 18.
- Thomas, R. E., M. Lindeberg, P. M. Harris, and S. D. Rice. 2007. Induction of DNA strand breaks in the mussel (*Mytilus trossulus*) and clam (*Protothaca staminea*) following chronic field exposure to polycyclic aromatic hydrocarbons from the *Exxon Valdez* spill. *Marine Pollution Bulletin* 54(6):726-732.
- Trust, K. A., D. Esler, B. R. Woodin, and J. J. Stegeman. 2000. Cytochrome P450 1A induction in sea ducks inhabiting nearshore areas of Prince William Sound, Alaska. *Marine Pollution Bulletin* 40(5):397-403.
- Wiens, J. A., R. H. Day, S. M. Murphy, and K. R. Parker. 2001. On drawing conclusions nine years after the *Exxon Valdez* oil spill. *Condor* 103(4):886-892.
- Wolfe, D. A., and coauthors. 1994. The Fate of the Oil Spilled from the *Exxon Valdez*. *Environmental Science & Technology* 28(13):A560-A568.

Chapter 6 CONCEPTUAL MODELS

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CONCEPTUAL MODEL DEVELOPMENT

Our overall goal is to construct a set of hierarchical conceptual ecological models for the Gulf Watch Alaska program of the Northern Gulf of Alaska ecosystem to represent current state of knowledge about system structure and dynamics, build a framework for key hypotheses guiding research, identify data gaps and research needs, and offer tools to connect management objectives with scientific objectives. Our approach builds on a hierarchical structuring of modeling efforts. The initial stage was set with development of a general conceptual ecosystem model for the study system. The general modeling effort will be followed by a set of meso-scale sub-models representing different program components (benthic, pelagic, and environmental drivers) and integration of them. The meso-scale modeling effort will be followed by sub-models addressing focused management questions linked to our research objectives. Input from Principal Investigators of the Gulf Watch Alaska program is a key step of model development. Input has been gathered in workshops focusing on modeling, and using follow up queries and surveys.

GENERAL ECOSYSTEM MODEL

The goals of the conceptual modeling project during the first two years of the program were to develop analytical tools to support GWA modeling efforts and to craft a general umbrella model describing the GOA system representing the system knowledge of the program Principal Investigators. To elicit input, we conducted a modeling workshop during the first year of the program. The workshop had two primary objectives: develop a parsimonious, generic conceptual ecosystem model and test a rating tool to elicit expert opinion to assess linkages within conceptual sub-models. To generate the general model, Principal Investigators were asked to identify a set of components that belong in a generic conceptual model for the North Gulf of Alaska, and to generate a visualization linking those components together in a conceptual description of the North Gulf of Alaska. The challenge set forth was to create a general conceptual model for the Gulf of Alaska which contained the minimum amount of complexity necessary to describe the system. Participants were given a starting list of components and a skeleton of a conceptual model. Visualizations categorized model elements into forcing factors, biophysical processes, and biophysical components. The spatial arrangement of elements indicated the spatial scale at which the model components operated, and linkages represented interactions in the conceptual model. The consensus model was constructed by generating a conceptual model response matrix that was used to translate visual arrangement of model elements into a numeric matrix, generating a matrix for the spatial domain of elements on the master list, and using R script determining expert consensus on a) which elements from the master list should be retained in a final conceptual model, b) the spatial domain of elements retained in the final model, and c) the linkages between elements retained in the final model. The final step of the process involved reconstructing a visual representation of the conceptual model (Figure 6-1).

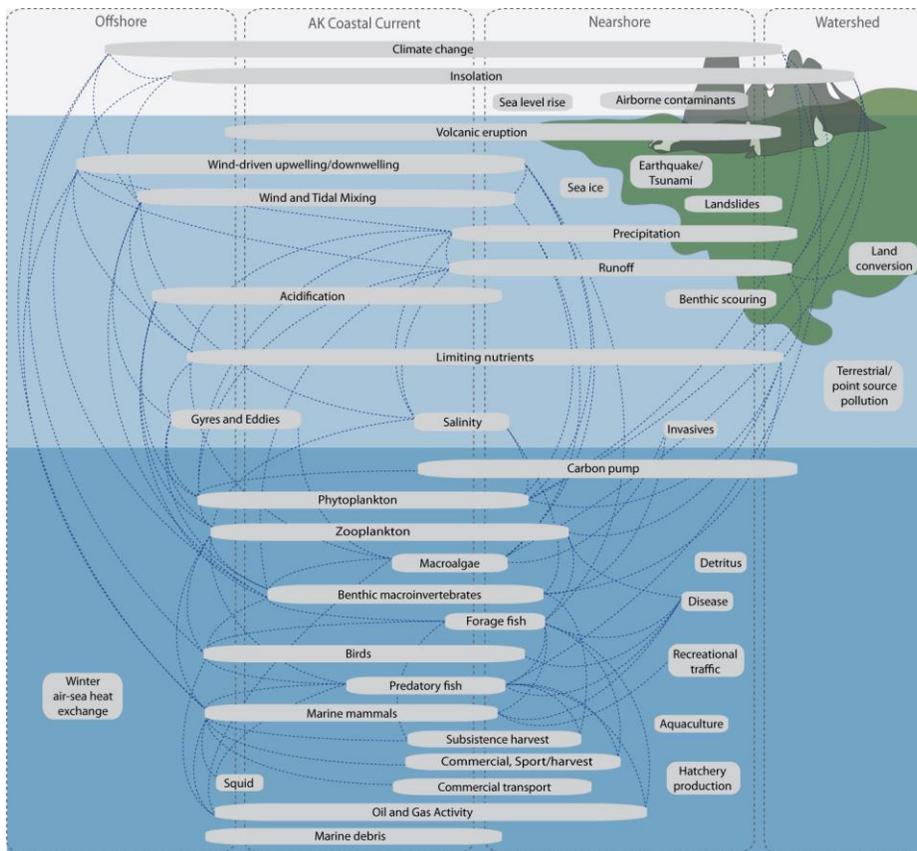


Figure 6-1. Conceptual ecosystem model of Northern Gulf of Alaska generated with expert input from Gulf Watch Alaska program investigators.

SUB-MODELS

The second objective of the first phase of the modeling effort was to develop rating tools to synthesize expert input to assess linkages in conceptual models. We developed a quantitative rating tool to assess linkage properties for iterative updating of our generic ecosystem model and for development of sub-models. To test the tool, we conducted an exercise during the modeling workshop and asked Principal Investigators to rate properties of linkages (strength, spatial scale, temporal scale, variability, and state of knowledge) in an example conceptual ecological sub-model, using rating scales provided. Input was entered into response matrices and processed in the R statistical programming environment. We developed threshold rules to determine whether a linkage should be retained in a final consensus model, used the mean linkage rating value amongst those respondents who included a retained linkage to reflect a consensus rating, and assessed group agreement by calculating the standard deviation of responses for a retained linkage. The linkage rating system will be used to quantify expert input in sub-models.

Our conceptual modeling continues with development of a series of sub-models to explore hypotheses among the key program components: benthic (Sub-model 1), pelagic (Sub-models 2, 3), and environmental drivers (Sub-model 4). The sub-models will be nested in the general ecosystem model (Figure 6-2.)

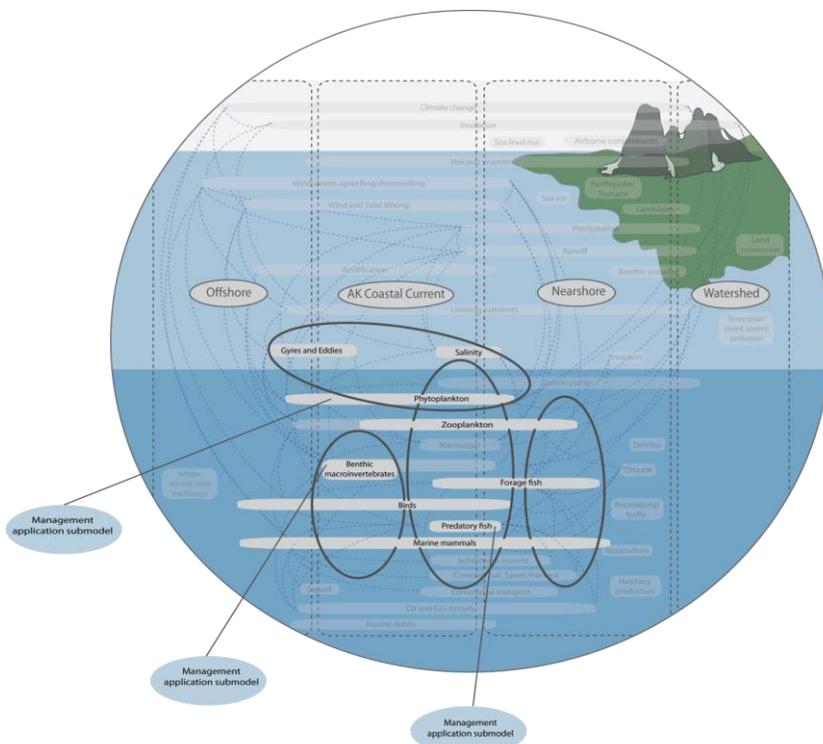


Figure 6-2. Conceptual universe of hierarchical model development structure. The large circle represents the umbrella model. The four circles within represent plans for ecological sub-models (nearshore model, forage fish model, phytoplankton model, and whale predation model). The external circles indicate components selected to date for focused management application sub-models. The diagram is intended as a visual map of modeling plans and does not contain all details intended for each of the sub-models.

Sub-model 1: Key Trophic Linkages in Nearshore Northern Gulf Ecosystems

The benthic nearshore model will examine the impact of changes in invertebrate prey fields on consumers of interest as measured by a suite of behavioral and demographic performance metrics. The overall goals of the modeling effort are to organize understanding about trophic linkages in the nearshore system, and the strength of relationships between invertebrates and consumers of interest, provide semi-quantitative simulation models to forecast consumer population outcomes/effects on consumer performance metrics resulting from changes in invertebrate prey fields, identify data gaps, and prioritize research to fill data gaps. A unique aspect of this modeling approach is that considerable empirical, quantitative information

exists on diet compositions for the consumers of interest and energetic requirements may also be available for consumer taxa.

Sub-model 2: Ecological Linchpin with Forage Fish Abundance

This conceptual sub-model focuses on the dynamics of a suite of forage fishes found in the Northern GOA. The sub-model examines linkages among forage fish prey, a suite of selected forage fish species, and higher trophic species populations. Salmon and other pelagic, marine forage fishes such as capelin, sand lance, and herring play important roles in the marine food web as predators, competitors, and prey. These connections, when examined through functional groups or shared similarities (i.e. examining loss of shared prey items across multiple species) can provide unique insights into food web dependencies and future management considerations (Anderson and Piatt 1999, Mueter and Boldt 2007, Hatch 2013, Springer and van Vliet 2014). Thus, this sub-model will explore a key trophic element of the GOA ecosystem and will be linked to management needs for coastal communities relying on fisheries for their economy.

The following linkages are considered for exploration in this sub-model:

- Linkages between selected forage fish abundance and environmental indices, i.e. El Niño southern oscillation, Pacific decadal oscillation, sea surface temperature (Anderson and Piatt 1999, Eslinger et al. 2001, Mundy 2005, Rose 2005)
- Linkages between abundance and distribution of copepods, pink salmon, and zooplanktivorous seabirds (Springer and van Vliet 2014).
- Linkages between forage fish and their predators, including linkages between forage fish and omnivorous seabird abundance or productivity (Hatch 2013, Springer and van Vliet 2014)

Sub-model 3: Top-down Control with Humpback Whale Predation

Much speculation regarding controlling factors for schooling and highly fecund fishes, such as Pacific herring, has focused on bottom up factors including availability of prey and suitable habitat. An alternative hypothesis with supporting evidence suggests that increasing predator populations may be acting as a top down controlling agent for these fish (Heintz et al. 1993). This conceptual sub-model explores the relationships between humpback whale prey types and seasonal patterns that can lead to a better understanding of the influence that predation may have on suppressed, economically important fisheries. Current understanding about the processes affecting herring-whale dynamics in the Northern GOA was explored in a sub-model exercise rating properties of linkages in a zooplankton-herring-whale sub-model system. Linkage properties included assessment of positive or negative impact from the upstream to downstream component, the strength of the linkage, the degree of stability of the linkage, the temporal and spatial scales at which a linkage operates, and the state of knowledge about the linkage. Consensus model results are presented in Figure 6-3. Additionally, the pelagic team has explored movements and distribution of humpback whales in Prince William Sound using conceptual modeling approaches, to explore humpback whale distribution and impacts on the Northern GOA ecosystem, and to identify gaps of data.

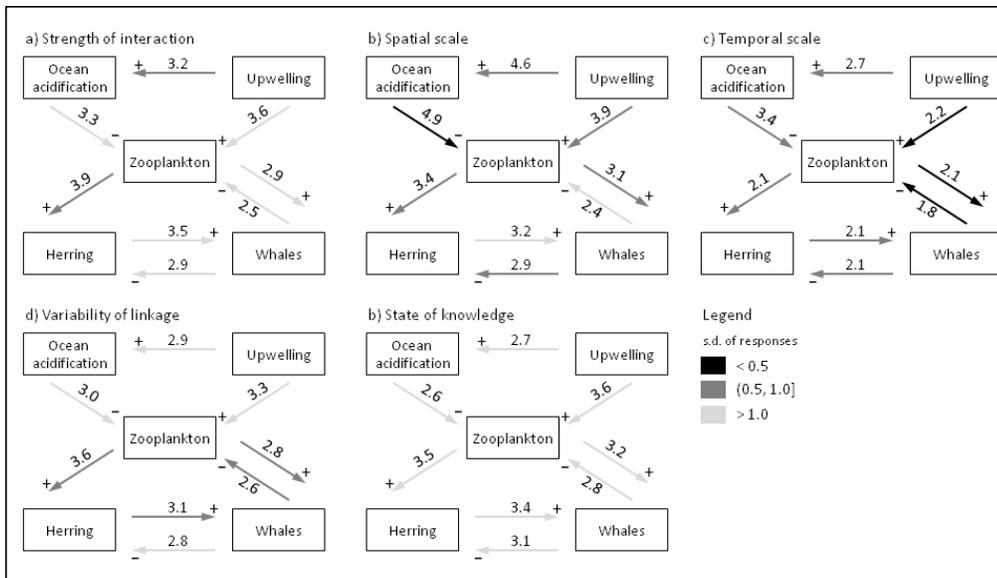


Figure 6-3. Consensus model results for the herring-whale model. A linkage of $X \rightarrow Y$ indicates X affects Y , with the direction of effect (positive or negative) indicated on linkage arrows. A given linkage was retained in the consensus model if three or more respondents included it. Numeric values represent mean ratings amongst participants who rated a linkage; possible values ranged from 1.0 to 5.0 (see Supplemental Text S1. Linkage arrow colors correspond to the level of agreement by respondents about a given linkage rating as measured by the standard deviation of ratings.

Sub-model 4: Bottom-up Control with Environmental Forcing on Plankton Populations

This conceptual sub-model focuses on plankton production and the various environmental conditions that are thought to act as drivers of primary and secondary production in the northern GOA. Levels of primary production are related to nutrient availability and solar input. Factors that influence these aspects include levels of stratification and mixing related to freshwater input, wind mixing, topography, and upwelling of nutrients (Mann and Lazier 2006). The strength of the winter Aleutian Low Pressure (ALP) system is strongly coupled to the strength of the Alaskan Coastal Current (ACC). The strength of the ACC is strongly coupled with the magnitude of upwelling to the shelf and nearshore environments –thereby providing nutrient input to these areas. A strong ALP generally is associated with strong winter wind patterns, a strong ACC, greater coastal downwelling, greater winter precipitation and warmer temperatures (Hollowed et al. 2001, Mundy 2005). Temperature is considered a strong driver of the timing and duration of the zooplankton bloom as well as phenological variability and quantities of lipid stores (Mackas et al. 2007). This sub-model will be exploring ecosystem responses to changing climate and, because plankton production is a primary source of energy conversion for higher trophic levels, the sub-model will have key ties to other models addressing higher trophic levels and associated management needs for coastal communities.

The following concepts represent processes that are considered in the development of the sub-model:

- Linkages between pressure systems and wind patterns under various climate regimes

- Linkages between wind patterns, precipitation, and stratification under various climate regimes
- Linkages between timing of freshwater runoff and distribution of primary production
- Linkages between stratification, nutrient availability, and temperature under various climate regimes
- Linkages between variation in nutrient circulation and primary production
- Linkages between temperature, light availability and life cycle timing
- Linkages between life cycle timing and implications for the ecosystem under climate changes

MANAGEMENT-LINKED SUB-MODELS AND DECISION SUPPORT TOOLS

The final phase of the conceptual and decision modeling effort during the current five year program will focus on 1) development of sub-models addressing selected management questions linked to Gulf Watch Alaska long-term monitoring program, and 2) development of decision support tools to organize and evaluate monitoring variables for long-term planning of monitoring efforts. The focus of the selected management linked sub-models will be developed based on stakeholder input on current management questions, and these models will be linked to the ongoing conceptual modeling efforts (Figure 2.). The models explore research needs relating to management objectives, and provide a framework for using decision analysis tools to consider management objectives and stakeholder input in monitoring plans. We anticipate working on these focused sub-models during 2015-2016.

Structured decision support tools will be used to develop an adaptive framework to guide monitoring efforts in long-term. Decision support tools offer techniques to establish a planning framework to guide monitoring efforts to identify and track changes due to natural variability and anthropogenic influences in the Gulf of Alaska ecosystem over the next two decades. We will develop decision models to identify a suite of potential scenarios and impact pathways, and construct an adaptive framework to guide scientific study and monitoring efforts to support management of resources based on indicators of change. The framework will offer adaptive guidance to monitoring data collection, based on learning contribution by the monitoring conducted by the Gulf Watch Alaska program. Using the framework and linkages to management needs, monitoring protocols will continue to be developed to measure and detect change relative to management objectives and long-term baselines established by our monitoring effort. Our ongoing conceptual modeling efforts will contribute to the development of the adaptive framework by characterizing current understanding of linkages between drivers and responses, and predicted effects and indicators of change. Input from scientific experts and resource managers will be incorporated into the framework. We will develop the structure and template for the adaptive framework using conceptual and decision modeling tools during 2015-2016, and the process will form a planning framework for the program over the next two decades.

References

- Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift.pdf. *Marine Ecology Progress Series* 189:117–123.
- Eslinger, D. L., R. T. Cooney, C. P. Mcroy, A. Ward, T. C. Kline, E. P. Simpson, J. Wang, and J. R. Allen. 2001. Plankton dynamics: observed and modelled responses to physical conditions in Prince William Sound, Alaska. *Fisheries Oceanography* 10:81–96.

- Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. *Marine Ecology Progress Series* 477:271–284.
- Heintz, R., J. Moran, J. Vollenweider, J. Straley, K. Boswell, and J. Rice. 1993. Humpback Whale Predation and the Case for Top-Down Control of Local Herring Populations in the Gulf of Alaska.
- Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific basin climate variability and patterns of Northeast Pacific marine fish production. *Progress in Oceanography* 49(1-4):257–282.
- Mackas, D. L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. *Progress in Oceanography* 75(2):223–252.
- Mann, K. H., and J. R. N. Lazier. 2006. *Dynamics of marine ecosystems*, 3rd ed. Blackwell publishing, Oxford, UK.
- Mueter, F., and J. Boldt. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. *Canadian Journal of ...* 927:911–927.
- Mundy, P. R. 2005. *The Gulf of Alaska Biology and Oceanography*. P. R. Mundy, editor. Alaska Sea Grant College Program, University of Alaska Fairbanks.
- Rose, G. 2005. Capelin (*Mallotus villosus*) distribution and climate: a sea “canary” for marine ecosystem change. *ICES Journal of Marine Science* 62(7):1524–1530.
- Springer, A. M., and G. B. Van Vliet. 2014. Climate change , pink salmon , and the nexus between bottom-up and top-down forcing in the subarctic Pacific Ocean and Bering Sea. *PNAS*:1–9.

Chapter 7 PROGRAM SUMMARY AND RECOMMENDATIONS

One of the greatest strengths of the Gulf Watch Alaska ecosystem monitoring program is that it provides baseline data to inform management of potential and observed species responses to natural and anthropogenic perturbations. The consortium-based approach of the Gulf Watch Alaska team fosters integration and improved communication across disciplines, which facilitate better understanding of marine ecosystem functioning and response to change. The team brings a wealth of experience, knowledge, and extensive time-series data into a single forum that continues to develop novel approaches to meeting the program goals of collecting long-term ecological data and providing the information for resource management. Synthesizing the large amount of data collected in the EVOS-affected region under EVOS Trustee Council and agency programs is a challenging task, particularly since monitoring efforts vary by sub-region, species, and sampling intensity (in time and space). This report provides an initial synthesis effort at the mid-point of the first five-year phase of the Gulf Watch Alaska program. The development of the report has itself sparked valuable discussions within and between Gulf Watch Alaska components and with the Herring Research and Monitoring program. We look forward to continuing and expanding those integration efforts as the program moves forward.

This chapter summarizes the key science findings from the Gulf Watch Alaska program synthesis (more details are provided in the earlier component chapters) and provides initial recommendations for future monitoring efforts.

MONITORING HIGHLIGHTS AND ECOLOGICAL SIGNIFICANCE

ENVIRONMENTAL DRIVERS

The Environmental Drivers component has focused on describing several key properties that appear common to the Gulf Watch Alaska area. In this section we summarize these findings, provide the mechanisms responsible for these (where known) and conclude with their potential ecological implications.

1. $0.20\text{ }^{\circ}\text{C decade}^{-1}$ temperature *increase* at surface and over upper 100 m
2. $0.15\text{ }^{\circ}\text{C decade}^{-1}$ temperature *increase* at between 100 - 200 m
3. 0.15 decade^{-1} salinity *decrease* at surface
4. 0.05 decade^{-1} salinity *decrease* over upper 100 m
5. 0.025 decade^{-1} salinity *increase* over 100 - 200 m
6. There is strong evidence of bottom-up forcing of phytoplankton and zooplankton abundance, and that timing and composition are related to the physical environment. Zooplankton density is significantly related to phytoplankton density on an annual basis.
7. There is strong interannual variability in physical variables and the plankton, even between adjacent years. Interannual variability is much greater than the variations associated with trends.
8. The developmental timing of copepods is strongly driven by temperature and that will influence when their peak abundances occur.

These findings imply a number of additional physical and/or geochemical changes for the northern Gulf of Alaska. Stratification is increasing as a consequence of the salinity trends, and the onset of springtime stratification that triggers the spring bloom may occur earlier. The nutrient regime should also be changing with increasing discharge. Within the euphotic zone, the iron supply is increasing but the nitrate supply is decreasing. In contrast, nitrate concentrations below the euphotic zone are increasing, although it is not clear if this increase can ever be made available to the primary producers given the changes in stratification. The freshening of the upper ocean implies a decrease in total alkalinity or the buffering capacity at the surface due to increasing coastal discharge, while the increasing sub-surface salinities are accompanied by lower pH waters that may be undersaturated with respect to aragonite

In aggregate these changes will affect primary and secondary production. If these trends continue, we expect a decrease in ocean productivity, although we cannot ascribe a time scale to the decline. If stratification is occurring earlier in spring, the spring bloom may be influenced by light availability and phytoplankton community structure may change. Changes in the seasonal phasing of the spring bloom or in metabolic rates due to a warming environment could lead to a timing mismatch between prey and predators that extends throughout the trophic system. The phytoplankton and zooplankton community structure are expected to change with the nutrient supply. Finally, there are a number of zooplankton species, such as pteropods, that are critical prey to salmon. These organisms appear particularly susceptible to the negative effects of ocean acidification.

PELAGIC ECOSYSTEMS

The initial three years of work within the pelagic component have been informative and productive. Some projects were initiated within the Gulf Watch Alaska program and are in their infancy, but have quickly developed protocols and acquired three years of data. Other aspects were well established prior to Gulf Watch and continue to monitor long-term population trends and to detect change. Major findings from the first five years include: (1) killer whales are good indicators of long-term trends and sensitive to perturbations such as oil spills for which consequences may include extinction; (2) humpback whale predation in PWS can exert top-down controlling pressure equivalent to the impact of a directed fishery; (3) forage fish monitoring requires multiple methodologies to accommodate their diverse life histories; (4) analysis of 12 years of boat-based marine bird surveys spanning 25 years since 1989 found that during summer, changes in pelagic food webs likely contributed to the delayed recovery of some piscivorous marine bird taxa; and (5) as much as 10% of the adult herring biomass can be removed by avian predators during winter months, suggesting that predation by marine birds also may exert a top-down effect on herring. Current monitoring work leverages the potential for broader ecological studies that will draw connections between individual species as well as the components of this program.

NEARSHORE ECOSYSTEMS

The nearshore is considered an important component of the system because it provides a variety of unique habitats for resident organisms (e.g. sea otters, harbor seals, shorebirds, seabirds, nearshore fishes, kelps, seagrasses, clams, mussels, and sea stars); nursery grounds for marine animals from other habitats (e.g. crabs, salmon, herring, and seabirds); feeding grounds for important consumers, including killer whales, harbor seals, sea otters, sea lions, sea ducks, shorebirds, brown bears, and many fishes and shellfish; a source of animals important to commercial and subsistence harvests (e.g. marine mammals, fishes, crabs, mussels, clams, chitons, and octopus); an important site of recreational activities including fishing, boating, camping, and nature viewing; a source of primary production for export to adjacent habitats

(primarily by kelps, other seaweeds, and eelgrass); and an important triple interface between air, land and sea that provides linkages for transfer of water, nutrients, and species between watersheds and offshore habitats.

Within this component, as well as in related work, we have confirmed that the food web-based design for nearshore monitoring can address questions about sources of variation at several spatial and temporal scales. The sampling design allows for broad scale inference across the GOA, and monitors producers and consumers, with the capacity to inform causes of change. Major findings from the first five years include: (1) the structure of rocky intertidal communities is influenced by tidal elevation and region, with static drivers also contributing to variation, and (2) over the period 2008-2013, mussel abundance declined at study areas across the Gulf of Alaska, suggesting the influence of large-scale drivers although local variability in abundance was also of importance.

RECOMMENDATIONS FOR FUTURE WORK

The Gulf Watch Alaska and Herring Research and Monitoring programs are currently beginning the fourth year of the first of four, five-year funding cycles. New results are emerging that enhance and refine our knowledge of the state and function of the northern Gulf of Alaska. Due to the inherent spatial and temporal variability in the system, many of the questions identified in the initial research proposals can only be addressed through continued monitoring and this should remain the focus of our efforts. However, some aspects of the program need refinement and information gaps necessary for making connections between species and components have become more apparent. In this light we make the following recommendations for future work.

OVERALL PROGRAM RECOMMENDATIONS

The EVOSTC-funded Gulf Watch Alaska program provides a unique opportunity to collect and integrate ecosystem data and make it available to state and federal resource managers. Initial synthesis efforts confirm the value of these long-term time series data for ongoing management of EVOS-affected species in the face of changing climate conditions. Support for cross-program data integration, in addition to data collection under individual projects, and for robust data management is critical to improve how EVOSTC data are used by resource managers. Monitoring activities, program management and data management services within Gulf Watch Alaska are currently highly leveraged with additional agency efforts, which may not be sustained indefinitely.

Efforts that we anticipate could be maintained within current program funding levels

We recommend sustaining long-term monitoring of marine conditions and species in the current program to build baseline data sets that can be used to assess post-spill ecosystem response, characterizing patterns and trends over decadal periods, along the GOA coast and between estuary and shelf environments. These include:

- Sustain current long-term monitoring of marine conditions and targeted species.
- Ensure robust data management services.
- Improve integration of data within *Gulf Watch Alaska*, with Herring Research and Monitoring program, and from other organizations.
- Target synthesis/conceptual modeling to develop decision support tools for improved resource management.

- Maintain outreach to managers, educators, and communities. Develop outreach products including annual “State of the Nearshore” or “Gulf Watch Alaska” reports.
- Maintain data coordination support for both programs.

Improve integration and synthesis through restructuring of currently funded projects, these include:

- Transition forage fish project to forage species monitoring/index development – linked with Herring Research and Monitoring. Improve understanding of bottom-up and top-down (predator diet) processes.
- Continue funding for science synthesis (currently through NCEAS working groups and conceptual modeling projects) through tools such as program post-doc (and graduate student) positions to conduct targeted efforts (also allows mentoring and knowledge transfer).

Projects requiring additional funds that will improve integration

We recommend several projects that will improve integration through analyses and higher-frequency monitoring:

- Provide capacity (staffing) to develop targeted data products and decision support (e.g. State of the GOA report, scenario planning with *Gulf Watch Alaska* time series).
- Establish temporally intensive nearshore/pelagic/environmental drivers monitoring site(s) at accessible locations (e.g. coastal labs) to allow high-frequency sampling throughout the year, including taking advantage of existing monitoring work such as the Middleton Island seabird assessment project.
- Use monitoring data to develop an understanding of important ecological processes and trophic relationships. Suggested mechanisms: collaborations with North Pacific Research Board, Bureau of Ocean Energy Management, or other entities:
 - Example: growth and recruitment of benthic invertebrates and algae, and performance of vertebrate consumers.
- Expand data management collaborations with trustee agency data centers to ensure a long-term (beyond EVOSTC program funding) data archive for EVOSTC-funded ecosystem data.
 - Examples include redundancy in data back-up and documentation of location of various data packages
 - Streamline processes to facilitate use of national archives/repositories (i.e. National Centers for Environmental Information conversion work in progress, NCEAS)

Projects that will not continue to the future

The analyses conducted for this report, combined with discussions during the joint EVOSTC science workshop with the Herring Research and Monitoring Program, show that these observations are valuable for resource managers. We therefore recommend continuation of monitoring with the exception of the following work:

- Studies evaluating exposure to lingering oil and status of recovery of harlequin ducks and sea otters have concluded as of 2014. Continued monitoring of oil on shorelines is proposed (see below). Note: continued monitoring of other metrics related to sea otters and harlequin ducks is ongoing as part of the Nearshore component, but will not involve captures or biomarker studies to assess exposure.

ENVIRONMENTAL DRIVERS COMPONENT

Both short- and long-term perspectives on this marine ecosystem would not be possible without sustained (multi-decade) and systematic (cross-region) observational efforts. Integrating the complementary sampling efforts within the Environmental Drivers component has enabled us to improve understanding of broad-scale (PWS, northern Gulf of Alaska shelf, and lower Cook Inlet) patterns in the physical environment and the plankton communities. Surface physical variables are coherent at periods longer than monthly time-scales, but coherence falls off rapidly at shorter periods. Recommendations for ongoing monitoring efforts include the following:

- Continue long-term monitoring projects.
- Install additional photosynthetically available radiation (PAR) sensors in the Gulf Watch Alaska sampling region including offshore (e.g., at Middleton Island) and inshore locations with easy logistic access.
- Determine appropriate temporal and spatial scales for monitoring to understand ecological changes through analyses of current datasets to more closely link across components and programs.
- Make more extensive nutrient measurements (temporally and spatially) in more places than currently measured in order to capture important intermittent upwelling events that affect primary production on the shelf, in Prince William Sound, and Cook Inlet.
- Spatial and temporal variation is high in the sampling design capable of making inferences across the GOA. Therefore we recommend establishing accessible temporally-intensive monitoring sites at logistically tractable sites (coastal labs) to improve the ability to interpret and apply nearshore data.
- Improve satellite ocean color-based estimates of coastal Chlorophyll-a by developing, validating, and applying coastal water algorithms appropriate for turbid water in the Gulf of Alaska.

PELAGIC ECOSYSTEMS COMPONENT

Key to this monitoring effort has been focusing on species that play a pivotal role in the pelagic ecosystem as trophic indicators for short and long-term ecosystem change. A sound foundation has been secured by continuation of long-term legacy data sets invaluable to understanding change (e.g., killer whales and seabirds). Future goals will be to continue these legacy data, refine our knowledge through integration, and find linkages to other ecosystem components.

Recommendations

- Continue to characterize long-term variability and population trends for all pelagic species. Enhance monitoring of killer whales by improving information on killer whale diets and connections to important fisheries (salmon) and marine mammals (sea lions, harbor seals).
- Further coordination (1) among the marine bird, humpback whale, and forage fish projects through integrated seasonal marine predator surveys and (2) between the Herring Research and Monitoring program, forage fish project, and environmental drivers component by conducting biennial validation in concert with aerial-acoustic forage fish surveys. Integration facilitates more

robust understanding of linkages between abundance and distribution of marine predators and their prey, and improves our ability to track biological responses to major perturbations in the Sound. Additional sampling would be required to examine seasonal changes in marine predator diets and foraging associations.

- Because the Middleton Island seabird diet index is the longest existing time series for forage fish abundance in the spill-affected area, as part of the forage fish project we recommend support for collaborative efforts with the Institute for Seabird Research and Conservation to maintain seabird diet monitoring efforts at Middleton Island.

NEARSHORE ECOSYSTEMS COMPONENT

Continued synthesis among Gulf Watch Alaska components, as well as directed research in association with monitoring activities, will further facilitate documentation of change, understanding functional relations, identification of sources of change, and forecasting of potential future conditions.

- Work with Environmental Drivers component to evaluate links between broad-scale physical oceanographic variation and key site-specific, nearshore variables, specifically temperature and salinity, as well as to develop methods to acquire local-scale data.
- Because of the major role of overwintering sea ducks in the nearshore food web, support winter marine bird surveys (directed at Gulf Watch Alaska nearshore study areas, and monthly surveys in Resurrection Bay) and collaborate with ADF&G surveys in Kachemak Bay.
- Conduct ShoreZone mapping of the study regions on a decadal timeframe to assess large scale changes in linear extent of biological zones in the nearshore.

LINGERING OIL COMPONENT

Although there currently is no evidence of continuing effects on Harlequin ducks and sea otters monitored under the Gulf Watch Alaska program, lingering *Exxon Valdez* oil remains within the beaches of PWS and elsewhere in the Gulf of Alaska. We do not recommend continuation of the existing studies on harlequin ducks and sea otters. The amount of lingering oil is small relative to the amount that originally stranded (Short et al. 2004b) and presumably has diminished since the last quantitative estimate was conducted in 2001 and 2003. As part of the Gulf Watch Alaska program, a lingering oil monitoring survey will be conducted in PWS during the summer of 2015 at 10-12 sites known to have persistent subsurface *Exxon Valdez* oil. We recommend continued long-term monitoring of these sites as well as sites outside PWS (Katmai and Kenai Fjords). Continued monitoring will allow us to observe oil persistence and assess the oil's weathering state through time. Because the rate of change is expected to be slow, intermittent evaluation (e.g., once every 5 years) likely will be adequate.

- Continue intermittent (5-year interval) monitoring of a subset of sites in Prince William Sound known to retain lingering oil, to quantify persistence and assess weathering over time.
- Monitor lingering oil at sites outside Prince William Sound, specifically shorelines in Katmai and Kenai Fjords National Parks.