Bering Sea Integrated Ecosystem Program (BSIERP) Study Plan

1. Summary

We offer a system of vertically integrated hypotheses and the means to test them. The hypotheses explain how climate controls the time and place of production of upper trophic level species. Models predict the likelihoods of population levels, trends and other attributes under several climate scenarios. Under warming or cooling, bottom-up control processes (water temperatures, sea ice extent and duration, strength and location of ocean currents and nutrient fluxes) determine the time and place of food production. Under warming, changes in time and place of food production lead to dominance of top-down control processes in the pelagic marine environment and the decline of benthic production, whereas cooling relaxes top-down control in the pelagic zone and increases benthic production. Our study focuses on understanding trophic interactions among: 1) colony-based foragers, 2) hot spot foragers, 3) pelagic forage species, 4) pelagic predators and 5) benthic predators. Hypotheses are tested in a linked set of spatially explicit, competing models that connect climate scenarios, physical and biological oceanographic models, a lower and upper trophic level ecosystem model and economic and management models. Models forecast changes in abundance of pelagic piscivores in response to changes in predators and prey and attendant economic and management consequences. Two-way connections between the program and communities, stakeholders and the region's body of local and traditional knowledge are enabled by outreach, education and community involvement projects. Our products enable testing and improved understanding of effects of climate change and management actions on the Bering Sea ecosystem.

2. Proposal Classification

A. Ecosystem Components: Lower Trophic Level Productivity, Fish and Invertebrates, Marine Mammals, Seabirds and Humans.

B. Keywords: trophic structure, ecological processes, zoogeography, climate, physical and chemical oceanography, atmospheric coupling, socioeconomics and indigenous cultures.

C. Geographic Location: Bering Sea. Terrestrial study locations: Akutan, St. Paul, Togiak, Emmonak, and Savoonga; and oceanographic domains: inner, middle and outer domains and the shelf break.

D. Reviewer Expertise Criteria: oceanography, climate, physical, chemical, biological and atmospheric sciences, modeling, statistical, numerical, ecosystems, marine mammals, seabirds, invertebrate zoology, ichthyology, fisheries management, economics, anthropology, zoogeography and fishing industries.

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Program Management **Leader:** NPRB

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4. Research Plan

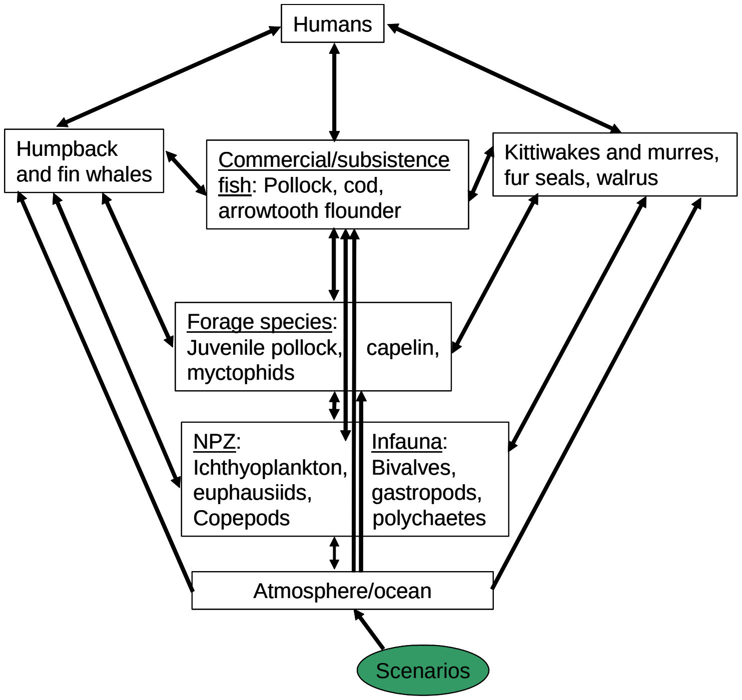
A. Project Title

Long Title: **Bering Sea Integrated Ecosystem Research Program (BSIERP) Study Plan**

Short Title: **BSIERP Study Plan**

B. Summary

We propose the means to test a system of hypotheses (Section D) that explain how climate controls the time and place of production of upper trophic level species (birds, fish and mammals) within the context of the physical and biological components of the Bering Sea (see adjacent figure). Hypotheses are tested by comparing new and existing observations to model predictions of the likelihoods of population levels, population trends and other attributes under differing climate scenarios. Warming of the Bering Sea climate is expected to alter the current geographic distributions and behaviors of humans, marine mammals, seabirds and fish by restructuring their habitats and food webs. Under warming or cooling scenarios, bottom-up control on time and place of food production is exerted by water temperatures, sea ice extent and duration and changes in strength and location of ocean currents and nutrient fluxes. Under warming, changes in time and place of food production lead to dominance of top-down control processes in the pelagic marine environment and the decline of benthic production, whereas cooling relaxes top-down control in the pelagic zone and increases benthic production. Our proposed NPRB work (Table 1) focuses on understanding trophic interactions among: 1) colony-based foragers (murres, kittiwakes, fur seals), 2) hot spot foragers (humpback and fin whales), 3) pelagic forage species (euphausiids, copepods, capelin, myctophids, juvenile walleye pollock) 4) pelagic predators (adult pollock, Pacific cod, arrowtooth flounder) and 5) benthic predators (walrus) (see adjacent figure). Hypotheses are tested in a linked set of spatially explicit models and competing models that include climate scenarios, physical and biological oceanographic models, a lower and upper trophic level ecosystem model and economic and management models. The linked model set forecasts changes in abundance of pelagic piscivores in response to changes in predators and prey and attendant economic consequences. Communities, stakeholders and the body of local and traditional knowledge will be strongly connected to the program through two-way communication mechanisms established by outreach, education and community involvement. Our vertically integrated study implements the ecosystem approach to management by providing the means for managers to test and continually improve ideas of the effects of climate change and management actions on a facsimile of the Bering Sea ecosystem.



Focal species examined in field studies and linked through models.

It is our expectation that the full scope of this research plan will be funded by the National Science Foundation (NSF) and the North Pacific Research Board (NPRB), with NSF primarily responsible for those physical and lower-trophic studies (Hypothesis 1, see Tables 1 and 2) that underpin the upper-trophic research that NPRB will fund (Hypotheses 2 – 5, see Tables 1 and 2).

This document describes the overall BSIERP study plan. The hypotheses, general approach and brief project descriptions are included. Separate documents describe study components in detail.

C. Project Responsiveness

Our overarching hypothesis is "C*limate change in the Bering Sea will alter the current geographic distributions and behaviors of humans, marine mammals, seabirds and fish by restructuring their habitats and food webs.*" Specific testable hypotheses are addressed through retrospective analyses, three years of new observations, full use of existing observations and modeling of climate and ecosystems (Table 1). Modelers and other project personnel will be advised by local and traditional knowledge and other information from community members through community involvement activities, as facilitated by *two-way* outreach and education. Our main approaches to build understanding of the Bering Sea ecosystem are to quantify variability in productivity of the focal species (pollock, cod, arrowtooth flounder, euphausiids, copepods, capelin, myctophids, murres, kittiwakes, fur seals, humpback and fin whales and walrus), to quantify the strength of trophic interactions among these species and to describe and quantify potential effects of climate variables on their productivity and the behavior and well being of human populations.

Five hypotheses explain our initial understandings of the relations among the components shown in the proposal summary figure (see Section D for full hypotheses): 1) Changes in atmospheric and ocean forcing cause changes in timing and location of food production, domain boundaries, stratification and circulation of the Bering Sea, 2) and the changing currents, domain boundaries and patterns of food availability have immediate consequences for spatial, temporal and feeding dynamics of pelagic fish, 3) resulting in top-down control of pelagic communities with attendant reductions in populations of place-based seabirds and mammals, 4) as well as further reductions or dislocations in certain species of fish, birds and mammals, 5) all of which have profound socioeconomic implications for all people who depend on the living resources of the Bering Sea. The projects that evaluate the hypotheses (Tables 1 and 2) are to be jointly funded by NSF (Hypothesis 1) and NPRB (Hypotheses 2-5).

Detailed hypotheses are given in Section D. Observational projects are labeled by the number of the primary hypothesis evaluated. For example, project O3.30 (Table 1) is project number 30, which primarily addresses Hypothesis 3, trophic interactions. Modeling projects are labeled M, but are not identified by hypothesis, as each model may be used to test multiple hypotheses. The hypothesis addressed by each proposed project is identified in Table 2.

C.1 Address Areas Identified by NPRB

The BSIERP provides the first comprehensive realization of the ideal of the *ecosystem approach to management,* EAM. The program is a model collaborative effort, integrating ongoing agency research programs in the Bering Sea with directed research aimed at understanding ecosystem processes, a critical prerequisite to implementing EAM. Also known as *ecosystem-based management* in the North Pacific Fishery Management Council and other venues, as broadly defined, EAM requires that harvest objectives for individual species be developed by using the best available information on the impacts of proposed harvest levels on associated non-target species in addition to the target stock biomass information. Although widely embraced in principle by entities such as National Oceanic and Atmospheric Administration (NOAA), the President's Ocean Commission and the U.S. Ocean Action Plan (Council on Environmental Quality), EAM has not yet been realized in practice. BSIERP is the kind of integrated fieldwork and modeling program needed to predict ecosystem-level impacts of the major harvest decisions for the Bering Sea in conjunction with predictions of responses of natural resources and humans to environmental variability on the scale of an ecosystem. We believe that the BSIERP's proposed explanations for phenomena of interest and its approach to iteratively testing the validity of each explanation against observation is the best possible approach now available for understanding the Bering Sea ecosystem given the available financial resources.

Until now, progress toward the ecosystem approach to management has been slow. The relationships among the abundance and distribution of dominant species and the major ecosystem processes that control them have been identified and tested piece-meal, usually two at a time. For example, such was the case in establishing the covariance of the Pacific decadal oscillation (PDO) and Alaskan salmon production (Mantua et al. 1997). In addition, the approach to defining such bivariate relations has been correlative, without explicit identification and testing of the biology and physics of the major ecosystem processes responsible for the biological phenomenon. Funding from NPRB provides a unique opportunity to bring together a broad spectrum of research and management expertise never before assembled to study the ecosystem in an integrated way. Indeed, the combination of expertise, matching observational platforms and the number of BSIERP personnel who are permanently based in the communities of the Bering Sea, create an unequaled opportunity for NPRB to be the catalyst that allows the most significant realization of the ecosystem approach to management to date, thereby achieving the purposes of the Bering Sea Integrated Ecosystem Research Program (BSIERP). The breadth and depth of the proposed research (Tables 1 and 2) is only possible due to the substantial matching contributions ($14.7M) of personnel, facilities and logistic support by the BSIERP institutions.

BSIERP concentrates its efforts on those major ecosystem processes that regulate the distribution and abundance of upper trophic level organisms, including humans, by controlling the time and place of food production (Hypotheses 1 – 5, Section D, Tables 1 and 2). Here, we present the consequences of warming to familiarize the reader with the major ecosystem processes of the five hypotheses. Bear in mind that under a cooling scenario, the quantitative changes in abundance for upper trophic level species are expected to be roughly opposite those of the warming scenario. Under a long-term warming scenario with early ice retreat, bottom-up control mechanisms (temperature, sea ice extent and duration, ocean currents and nutrient fluxes, see Hypothesis 1) set the stage for the emergence and dominance of top-down control processes in the pelagic marine environment and the decline of benthic production (cf. Hypothesis 3, see also Hypotheses 2 and 4). Increased heat content will increase the combined populations of the subarctic piscivores, arrowtooth flounder, pollock and cod, in proportion to expanded breeding grounds and increased availability of food during critical developmental stages (Hypothesis 2). Because arrowtooth flounder is not targeted by fishing, it is to become the dominant component of the biomass of the three subarctic piscivores in this study (pollock, cod and arrowtooth flounder). Arrowtooth flounder is predicted to be one of the principal agents of top down control in the Bering Sea, as predator and competitor of the now-dominant, but commercially exploited, pollock and cod (Hypothesis 3). Arrowtooth flounder are also agents of change as direct and indirect competitors of murres, kittiwakes and fur seals for their representative forage species (euphausiids, copepods, juvenile pollock, capelin and myctophids; Hypothesis 3).

Populations of murres and kittiwakes will fluctuate in the near term depending on locality of rookeries, but long term overall trends will be downward under warming. Murres, kittiwakes and fur seals will further decline due to competition from humpback and fin whales (cf. Hypothesis 4). Dislocation of feeding hot spots will disadvantage rookery-based murres, kittiwakes and fur seals, but work to the advantage of humpback and fin whales, further exacerbating direct and indirect competition between these two groups of species (Hypothesis 4). Dislocations and declines in kittiwakes, murres, fur seals, pollock and cod will distress human populations by increasing costs of maintaining a livelihood and obtaining food and by necessitating changes in the types of food taken and the means of harvest (Hypothesis 5).

The effect of ocean acidification on assimilation of essential carbonate compounds by species (e.g., crustaceans and pteropods) potentially is a major ecosystem process. Current knowledge of the magnitude and impact of ocean acidification in the Bering Sea is insufficient to permit incorporation of ocean acidification into our conceptual framework at this time. Research is currently being conducted by NOAA (NMFS and OAR) toward this end and a research cruise is planned for 2009 or 2010.

Benthic production is not a major focus of our observational work at this time, because of ongoing benthic observational work now funded by NSF ARC (A. Devol, NSF#0612436) that extends to 2010 and because gross changes in magnitudes and species composition of epibenthic production (Hypothesis 2.e) are readily apparent from observations and analyses routinely conducted by management agencies (NMFS and ADF&G). Project O3.30 (Table 1) also will test hypothesis 2.e against such survey data. A walrus patch dynamics study near St. Lawrence Island also will examine a benthic predator-prey relationship. Results of Project O3.30 and the ongoing benthic work will be used to strengthen our system of hypotheses and to propose a benthic observational program for implementation at the conclusion of the first BSIERP program.

By funding BSIERP, the NPRB would advance the evolution of natural resource management in the Bering Sea by at least a decade. While the U.S. government has recently adopted the goal of implementing the ecosystem approach to management in principle, practically speaking normal management agency function for federal agencies in the Bering Sea presently remains the assessment of stock size (production) for economically important or legally protected species and the assessment of their physical and geological habitats. The realization within federal management agencies of the ecosystem approach to management is an evolutionary process, with the first actual implementation being at least a decade away at the present pace of development, as judged by the out-year planning process for components such as LOSI, NPCREP and ship time. Furthermore, the first draft of an expert opinion on a national definition of EAM for fisheries was only recently circulated by NOAA (October 2006). Funding BSIERP would substantially advance the massive amount of often site-specific science necessary for EAM implementation.

The talent and desire necessary to implement EAM are evident in the credentials of the team assembled from scientists around the Pacific Rim. It is no accident that among all the regions of the U.S., it is only here in the Pacific that the first concrete steps have been taken toward EAM by adding limited ecosystem advice to a number of single species stock assessments. In funding BSIERP, the NPRB has the ability not only to vastly accelerate the implementation of the first full EAM operation in the nation, but also to define it scientifically through the peer review process. Scientific precedents established by publications resulting from BSIERP will lead the way to EAM for the nation, benefiting all resource-dependent communities and interests in the process and firmly cementing the reputation of the NPRB as the agent of positive change in natural resource management that it is.

D. Soundness of Project Design and Conceptual Approach

D.1 Background

The eastern shelf of the Bering Sea is a productive ecosystem, supplying nearly half of U.S. seafood catches, subsistence resources (fish, marine mammals and seabirds) for over 30 Alaska Native communities and forage for millions of seabirds and tens of thousands of marine mammals. This production is fueled by nutrients annually replenished from slope and oceanic waters across the very broad (>500 km) continental shelf (Stabeno et al. 2001; 2006). Seasonal sea ice extent currently divides the Bering Sea eastern shelf into two biogeographic provinces, which differ in production pathways. In the subarctic biogeographic province (south of the average-annual maximum sea ice extent), most primary production remains within the pelagic ecosystem and pollock is the dominant tertiary consumer (Macklin and Hunt 2004). In contrast, in the arctic biogeographic province, tight coupling between pelagic primary production and the benthos benefits benthic foragers such as gray whales, walrus and some seabird species (Grebmeier et al. 2006). The provinces' boundary varies in location on longer time scales (decadal or longer) and is expected to move northward as the region becomes warmer. The average southern edge of the maximum ice extent currently lies north of the Pribilof Islands (Byrd et al. in press).

Present data and climate projections from atmosphere-ocean models predict major loss of sea ice over the next decades (Overland and Stabeno 2004); the Bering Sea is particularly sensitive to global warming (Grebmeier et al. 2006). Recent relative temperature extremes in Alaska and adjacent waters (>2°C) represent the largest recent change on the planet (Hansen et al. 2006). However, these models and data also demonstrate large natural variability. Ecosystems will not only be affected by future warming and loss of sea ice, but also by the path of how warming occurs, such as, whether there will be a continued slow warming trend with little interannual variability versus a warming trend that incorporates wide swings in temperature and sea ice amounts. Regardless of interannual variation and short-term trends (Overland and Stabeno 2004), current climate models predict that by 2030, the warming trend due to greenhouse gases will surpass the range of natural variability (IPCC 2007).

While general patterns of production and biomass are well-known for the Bering Sea eastern shelf, the critical mechanisms linking physics to fish, apex predators and humans and the trophic interactions among fish, apex predators and humans are poorly understood. In addition, the spatial match-mismatch of forage species and predators will affect the strength of these links, especially because climate warming will move eco-regions northward. We now review what is known about mechanisms controlling production and trophic relationships in the Bering Sea eastern shelf.

The Coupling of Lower Trophic Levels to Fish Production

The strength of coupling between primary production and pelagic production varies among years and was hypothesized by Walsh and McRoy (1986) to be related to the timing of annual sea ice retreat. Hunt et al. (2002) presented critical evidence that late (after mid-March) sea ice retreat results in an early, ice-associated spring phytoplankton bloom that is mismatched with zooplankton production, then extended the Walsh and McRoy (1986) hypothesis to the control of overall pelagic fish production, which is predicted to oscillate between bottom-up and top-down mechanisms depending on the frequency of cold or warm years. In "cold" years of late sea ice retreat, recruitment of pelagic fishes is low because of poor larval survival (lack of food during their critical period), while in years when sea ice is frequently absent (or recedes early; "warm years") larval fish survival is good. At the beginning of a warm period, juvenile survival remains high because a majority of the spring primary production remains in the water column in the form of zooplankton biomass and recruitment remains higher than average until the biomass of predators (including cannibalistic adults) reaches a level that inhibits recruitment by new year classes. This pattern was developed using data from the southeastern shelf and is expected to apply to the central and northern shelf as maximum ice extent decreases. Sea ice, however, is not the only climate-related production driver (Mueter et al. 2006), which also includes water temperature, wind mixing and stratification, advection and biological interactions.

Water temperature strongly affects multiple trophic levels. For example, temperature determines the metabolic rates and production of all poikilotherms (plankton and fish). Zooplankton production during cold summers is 3-4% of that in a warm year (Coyle and Pinchuk 2002), potentially reducing growth and lipid stores so that age-0 fishes do not survive their first winter (Sogard and Olla 2000; Heintz and Vollenweider 2005; Farley et al. in press). In years with an extensive cold pool in the middle shelf, pollock generally shift toward the outer shelf (Mueter et al. 2004). Subarctic species are likely to advance northward and arctic species retreat under global warming (Stabeno and Overland 2001; Schumacher et al. 2003; Parmesan 2006; Stabeno et al. 2006).

Wind mixing and stratification affect the coupling of physics and lower trophic levels to fish production. Frequent strong storms during spring may reduce larval survival by interfering with feeding (Bailey and Macklin 1994; MacKenzie et al. 1994) and delay the open-water bloom. In contrast, occasional summer storms on the outer and middle shelf domains of the Bering Sea will replenish photic zone nutrients exhausted by the spring bloom and thus increase new production (Sambrotto et al. 1986; Stabeno et al. 2001; 2007). Increasing temperatures and decreasing summer storms (Stabeno and Overland 2001) have increased summer stratification, decreased summer phytoplankton blooms and decreased summer zooplankton production, potentially reducing availability of food for planktivorous fish, seabirds and marine mammals (Coyle et al. in press). As a result, even with early ice retreat, a match between spring bloom and zooplankton production and favorable conditions for ichthyoplankton during spring, conditions may not continue to favor fish production during summer. Increased summer temperatures and stratification over the middle shelf also may have caused the recent dominance of small copepods (Coyle et al. in press), which have ca. 1/30th of the carbon per individual than the larger copepods favored during colder regimes (Baier and Napp 2003). Smaller copepods likely increase foraging costs for spring-spawned fish such as pollock which depend on zooplankton production during their first summer to reach a critical size for first winter survival. Finally, summer winds in part determine the position and width of the inner front (Kachel et al. 2002), a region of weak vertical stratification, prolonged production and juvenile fish rearing.

Climate-mediated advection of larvae affects fish and shellfish recruitment in the Bering Sea (Wespestad et al. 2000; Rosenkranz et al. 2001; Wilderbuer et al. 2002) due to changes in surface wind patterns or combined changes in winds and geostrophic currents that transport larvae to favorable nursery grounds (Lanksbury et al. 2007), which may enhance feeding conditions or release predation pressure (Wespestad et al. 2000) at the nursery grounds. Advection and behavior also can influence fish survival when the cold pool causes vertical separation of cannibalistic adult pollock from their juveniles (Bailey 1989). Advection and sea ice persistence are not completely independent because ice melt contributes to the baroclinic flow over the shelf.

Biological interactions also can control fish production. The OCH tended to concentrate on adult pollock as the agents of top-down control, but the recent increase in Bering Sea arrowtooth flounder abundance (Wilderbuer and Nichol 2005) is cause for concern demonstrated by their role in the Gulf of Alaska ecosystem as predators of juvenile pollock (Bailey 2000; Hollowed et al. 2001). The exact mechanism for their recent increase in the Bering Sea is unknown. Pollock also prey on juvenile arrowtooth flounder, but fishing mortality is much less for arrowtooth flounder than pollock, so pollock may be differentially affected, especially if pollock recruitment declines (Aydin et al. 2006). When forage fish are strongly limited by top-down processes, there should be more zooplankton to support other planktivore populations (e.g., chaetognaths, jellyfish, sockeye salmon and baleen whales). In addition, interannual variability impacts pelagic lower trophic levels very quickly because of their short life cycles, while benthic communities and higher trophic levels are buffered to some extent by their longevity, creating lags in the system and motivating a long-term research effort.

The Importance of Higher Trophic Levels

Synoptic, multi-scale and multi-disciplinary field research is necessary to examine food webs and the effects of climate change on marine environments (Weimerskirch et al. 2003; Montevecchi et al. 2006; Scott et al. 2006). Apex predators such as predatory fish, seabirds, and marine mammals influence the food web and commercial fish production through both top-down control and competition. When the dominant forage in the food web is the juvenile stage of a commercial species (pollock), apex predators have a direct impact on the recruitment success of that species by removing juvenile fish from the system. During times of rebounding predator populations, their consumption of forage species may create periods or locations of intense competition between apex predators and commercial fish species.

Many piscivorous apex predators are central place foragers that benefit from reliable prey concentrations near their breeding sites for maximal reproductive success and offspring growth. For example, kittiwakes, fur seals and murres need reliable prey concentrations during the breeding, post-natal and post-fledging periods. At the Pribilof Islands, capelin virtually disappeared from fur seal, kittiwake and murre diets by the early 1980s, coincident with increased occurrence of pollock and sand lance during the 1980s and 1990s (Hunt et al. 2002); pollock has become almost uniquely important in the fur seal diet with some variation associated with foraging domain (Zeppelin and Ream 2006). In the late 1980s, capelin moved well north of the Pribilof Islands (Brodeur et al. 1999) and pollock, Pacific cod, rock sole and arrowtooth flounder also shifted northward (Hunt et al. 2002). Seabirds have higher reproductive success when provisioning chicks with capelin (Baird 1990) or other, lipid-rich forage species (Golet et al. 2000), implying that the carrying capacity for piscivorous seabirds has decreased (Hunt et al. 2002). Chick growth rates, mass at fledging, fat reserves at fledging and post-fledging survival are all dependent on the lipid content of the diet (Romano et al. 2006). Capelin, sand lance and herring generally have higher lipid content than juvenile gadids, such as pollock, Pacific cod and tomcod (Anthony et al. 2000). In addition, all forage fishes, regardless of taxonomic affiliation, have higher lipid content when foraging on abundant, lipid-rich zooplankton. As a consequence, seabirds have been widely recognized for their ability to indicate changes in marine ecosystems due to their sensitive dependence on food availability and quality (Boersma 1978; Crawford and Shelton 1978; Ricklefs et al. 1984; Cairns 1987; Croxall et al. 1999; Chapdelaine and Brousseau 1989; Monaghan et al. 1989; Harris and Wanless 1990; Hamer et al. 1991). Seabird response to these changes is reflected in changes in diet composition (Springer et al. 1984; Hatch and Sanger 1992; Ballance et al. 1997; Anderson and Piatt 1999; Bryant et al. 1999; Croxall et al. 1999; Carscadden et al. 2002; Suryan et al. 2002), foraging behavior (Cairns 1987; Burger and Piatt 1990; Suryan et al. 2000) and nesting success (Jodice et al. 2006). Seabirds are often monitored at their breeding colonies (e.g., Dragoo et al. 2003), yet they spend most of the year widely dispersed over vast areas offshore and indeed, non-breeding seabirds consume greater biomass than breeding birds (Hunt et al. 2000, 2005).

Nonetheless, a uniform response of all seabird rookeries to ecosystem-wide changes in the location and timing of food production in response to climate change is not envisioned by our hypotheses, as the strength of coupling of any given rookery to food resources depends on its location. Rookeries of significant interest are those that have evolved in close proximity to the ice edge. Specifically, seabird productivity at St. Paul Island has been linked to extent of sea ice. In years of little ice, seabirds did poorly (Byrd et al. in press). Overall trends in seabirds that breed in the Bering Sea are hypothesized to be negative under warming, with declines to be seen first in those rookeries with geographically limited food resources.

Large baleen whales were severely depleted by commercial whaling until the late 20th century (Clapham et al. 1999), but since protection was afforded, many populations have been increasing, including humpback and fin whales feeding in the Bering Sea and the Aleutian Islands (Moore et al. 2002; Zerbini et al. 2006). Whales consume large quantities of prey, so that their increased abundance likely will modify community structure through increased predation at mid-trophic levels and increased inter-specific competition among plankton and forage fish consumers (Bowen, 1997). Most data on Bering Sea baleen whale prey (Nemoto 1957, 1959, 1970) are outdated because the Bering Sea has undergone major climate and oceanographic (regime) shifts (e.g., Francis and Hare 1994; Overland et al. 1999; Trites et al. 2007). Trophic effects of predation by large whales cannot be assessed without updated research, including a description of the whale's foraging behaviour (i.e., functional response; e.g., Piatt and Methven 1992; Piatt et al. 1989) and prey and habitat characteristics.

Foraging behavior of seabirds and marine mammals can be linked to prey distribution and identifiable habitat features. In air-breathing vertebrates, finding concentrated prey patches are important to an individual's energy budget. Predictable prey locations reduce search time and thus energetic costs of foraging (Gende and Sigler 2006). Foraging Steller sea lions return to geographic locations where prey are reliably found (Sigler et al. 2004; Womble and Sigler 2006) and vary their dive behavior in response to oceanographic changes (Fadely et al. 2005). During the pup-rearing season of July-November, adult female fur seals generally exhibit rookery-specific foraging area segregation among several Bering Sea domains (Robson et al. 2004), with varying foraging strategies among domains (Call et al. in press). Foraging within different domains may influence reproductive success, as shorter maternal foraging trip durations are associated with increased pup growth rates that may also vary between warm and cold oceanic years (Banks et al. 2007). Planktivorous seabirds and baleen whales are dependent on reliable concentrations of prey (hot spots) that are affected by the climate-mediated processes described above (e.g., Croll et al. 1998; Lovvorn et al. 2001; Baumgartner et al. 2003).

D.2 Human Impacts and Effects on Humans

The Bering Sea ecosystem is affected by both direct and indirect human impacts including fishing, benthic habitat alteration and human-caused global warming. In turn, changes in the ecosystem, whether caused by natural variability, fishing, or warming, have an effect on those whose livelihoods depend on the productivity of the Bering Sea. Human population size around the Bering Sea has increased 7-fold since 1920 (Boldt 2006). The eastern shelf of the Bering Sea is a productive ecosystem, supplying nearly half of U.S. seafood catches, subsistence resources (fish, marine mammals, seabirds) for over 30 Alaska Native communities and forage for millions of seabirds and tens of thousands of marine mammals. This study addresses effects on humans through spatially integrated economic modeling, local and traditional knowledge and community involvement projects (see D.5 for project descriptions).

D.3 Species and Geographic Scope

Our study focuses on pelagic forage species (juvenile pollock, euphausiids, copepods, capelin and myctophids), colony-based foragers (murres, kittiwakes and fur seals) and hot spot foragers (humpback and fin whales) that are tied to a place, a benthic forager (walrus) and trophic interactions between these species, as well as adult pollock, cod and arrowtooth flounder. This species suite was chosen to span major upper trophic taxa (fish, seabirds and marine mammals), to encompass major upper trophic components (pollock, arrowtooth flounder, humpback and fin whales; Livingston 1993, Aydin and Mueter in press), forage species (juvenile pollock, euphausiids, copepods, capelin and myctophids; Aydin and Mueter in press) and commercial fishery value (pollock and cod; Hiatt 2006) and to include place-based foragers likely to be affected by climate-induced relocation of prey (murres, kittiwakes, fur seals, humpback and fin whales). These populations primarily are distributed on the southeast Bering Sea shelf, but may range onto the slope (e.g., cod, pollock), the northeastern Bering Sea (e.g., pollock, Ianelli et al. 2006), or the Gulf of Alaska (e.g., cod, Shimada and Kimura 1994). Populations of kittiwakes and murres are limited in their distribution to a relatively small portion of the shelf and/or slope during the breeding season and may leave the region during the non-breeding season.

D.4 Conceptual Framework/Hypotheses

Climate models predict warming over the next 30 years (IPCC 2007). Predictions from climate models show no indication of a strengthening of summer winds. In fact, there has been a decrease in wind strength and lengthening of summer conditions over the last decade (Overland and Stabeno 2004; Stabeno and Overland 2001). Projected warming on the southeastern shelf of the Bering Sea will profoundly alter ecosystem structure by changing pathways of energy flow and the spatial distribution and species composition of fish, seabird and marine mammal communities, thereby affecting commercial and subsistence fisheries.

1. Climate-induced changes in physical forcing will modify the availability and partitioning of food for all trophic levels through bottom-up processes. Specifically:
   a. Earlier sea ice retreat expected as a result of warming will result in a later (May-June), warm-water spring phytoplankton bloom, increased coupling with zooplankton and greater pelagic secondary productivity. Benthic secondary productivity will decrease.
   b. Reduced frequency and intensity of summer storms will reduce surface mixing and increase sea surface temperature, thereby increasing stratification. A substantial decrease in summer winds will result in a mixed layer that is shallower than the euphotic zone, extensive subsurface primary production and depletion of nutrients in the entire water column. There will be no fall phytoplankton bloom. A moderate decrease or no change in the intensity of summer storms will reduce replenishment of nutrients to the euphotic zone, lowering summer primary and secondary production. Both scenarios will reduce juvenile fish production by reducing their condition (energy density) and over-wintering capability.
   c. Earlier spring transition will lengthen the period of time of organized onshore flow along the Alaska Peninsula, thus transporting larvae away from outer domain piscivores.
2. Climate and ocean conditions influencing water temperature, circulation patterns and domain boundaries impact fish reproduction, survival and distribution, the intensity of predator-prey relationships and the location of zoogeographic provinces through bottom-up processes. Specifically:
   a. As heat content increases, the area suitable for spawning and foraging by subarctic species will expand northward and subarctic species will occupy areas formerly occupied by Arctic species.
   b. Reduced cold pool extent will increase overlap of inner domain forage fish and outer domain piscivores.
   c. Strength of frontal boundaries will weaken due to absence of the summer cold pool, allowing expansion of the inner domain and juvenile and forage fish habitat there. Weaker winds will enhance this effect.
   d. Sporadic reversals to cold conditions (e.g., 1999) will have strong effects on the subarctic community and result in increased interannual variability in abundance and pelagic productivity of piscivorous fish, seabirds and marine mammals.
   e. Expected decreases in benthic productivity will negatively affect feeding and survival of small flatfish and crab thereby lowering population levels.
3. Later spring phytoplankton blooms as a result of early ice retreat will increase zooplankton production, thereby resulting in increased abundances of piscivorous fish (pollock, cod and arrowtooth flounder) and a community controlled by top-down processes [Oscillating Control Hypothesis] with the possible trophic consequences:
   a. Competition with abundant, piscivorous fish species for forage species will lead to a decline in murres, kittiwakes and fur seals.
   b. Growing populations of humpback and fin whales increasingly will both consume and compete with forage fish (juvenile pollock) for zooplankton (euphausiids and copepods). By reducing the prey base of forage fish, whales not only reduce the amount of forage fish available to other predators, but also their quality (lipid content).
   c. In a top-down control community, fishing will reduce the degree of top-down control of forage species (including juvenile pollock) by adult pollock, cod and arrowtooth flounder. Owing to

light exploitation rates, top-down control by arrowtooth flounder will increase, as will their level of competition with piscivorous fish, seabirds and marine mammals. As a result of these two processes, arrowtooth flounder will determine ultimate community composition, such that the climax community will be arrowtooth flounder-dominated (similar to the Gulf of Alaska).

4. Climate and ocean conditions influencing circulation patterns and domain boundaries will affect the distribution, frequency and persistence of fronts and other prey-concentrating features and thus the foraging success of marine birds and mammals largely through bottom-up processes. Specifically:
    a. Climate-ocean changes will displace predictably located, abundant prey (hot spots) necessary for successful foraging by central place (seabirds and fur seals while nurturing young) and hot spot (baleen whales, walrus) foragers.
    b. Central place foragers will shift their diet, foraging locations or rookery locations to increase foraging opportunities (based on differential foraging success).
5. Climate-ocean conditions will change and thus affect the abundance and distribution of commercial and subsistence fisheries. Specifically:
    a. For commercial fishermen, these changes will lead to: 1) a change in home ports and distribution of fishing vessel rents, 2) vessels traveling further, incurring greater fuel costs and peril at sea and 3) greater burden on smaller vessels.
    b. For subsistence users, these changes will lead to: 1) greater reliance on owners of larger vessels that can travel farther to harvest and distribute subsistence goods, 2) decreased consumption of species with decreased local abundance and 3) adoption of new species into the diet as these species colonize local areas.
    c. Current management strategies for fish, seabirds and marine mammals in the Bering Sea are robust to climate scenarios (range of frequencies of cold and warm years) and associated range of trophic relationships and spatial redistributions.

D.5 Project Descriptions

The Project Description section (D.5) plus the Linked Modeling (D.6) section that follows describe the field projects, retrospective analyses and models (Table 1) which together form our proposal. Both NPRB and NSF projects are described. All project components are connected, with research products from field projects and retrospective analyses (‘O’ prefix, e.g., O1.1) providing inputs to a suite of physical, biological, ecosystem and socioeconomics models (‘M’ prefix, e.g., M.3); these models in turn are linked together (Fig. 1) and provide scenarios and advice for management of subsistence and commercial fisheries. Project links to hypotheses also are shown in Table 2. An additional purpose of Figure 1 and Tables 1 and 2 is to show the connections between research activities, focal species and ecosystem processes (Item D.(1)(b) of the RFP). Estimates of quantitative changes in major ecosystem processes are provided by our observational projects and models associated with the hypothesis in which they operate, as shown in Table 2.

Study designs, sample sizes and analytical methods are based on standard statistical (e.g., Zar 1999), quantitive fisheries (Quinn and Deriso 1999) and quantitive ecological (Hilborn and Mangel 1997) methods for all projects. Sample sizes also are based on previously published reports and are expected to provide adequate precision for hypothesis testing and for parameter estimates to be used in the modeling efforts.

Biophysical Moorings: This project is a continuation of a long-term partnership between NOAA and NPRB. Moorings (Fig. 2) have been deployed at M2 since 1995 and M4 since 1996. The other sites provide shorter records. These moorings, together with observations along the 70-m isobath, are core to the long-term observations on the Bering Sea shelf. All four moorings are deployed on the 70m isobath. Key findings including the OCH, timing of spring bloom, the magnitude of increased temperature (>2°C) and stability in the nutrient supply have all been a result of the data collect on these moorings. This project (O1.1) will continue the time series of temperature, salinity, fluorescence, currents, zooplankton abundance (TAPS-8), nitrate, oxygen, turbidity and light (PAR) collected by instruments on the moorings. Data from these moorings are also critical to model verification. Products include mixed layer depth, heat content, temperature, position of the transition between southern pelagic-dominated shelf and northern benthic-dominated shelf, advection, nutrient supply and timing of the spring phytoplankton bloom.

Spatial Distribution of Forage Species (pollock, euphausiids, myctophids and capelin): This project builds on evidence for the impact of climate forcing on the spatial and temporal changes in ocean temperature, oceanic fronts, mixed layer depth and currents and their influence on fish distribution and growth (Kotwicki et al. 2005; Hollowed et al. 2007; Mueter and Litzow in press). These findings underscore the importance of considering the effect of ocean forcing on fish and euphausiids at different spatial and temporal scales (Bailey et al. 2005; Duffy-Anderson et al. 2005). The project objective is to understand the response of fish and euphausiids to shifts in the characteristics of ocean habitat and use that understanding to model the impacts of climate change on their spatial and temporal distribution. This project focuses on spatial patterns of pollock, euphausiids, myctophids and capelin.

Spatial patterns of the forage species including pollock, euphausiids, myctophid and capelin will be determined from standard NOAA acoustic (O2.26 [Table 1, Fig. 1]) and surface trawl (BASIS [Bering Aleutian Salmon International Survey]) (O2.23) surveys. Acoustic surveys are designed to estimate pollock abundance (Honkalehto et al. 2002), have been conducted in the middle and outer domains of the eastern Bering Sea shelf (Fig. 2) approximately biennially since 1979 and are planned for 2008, 2009 and 2010. Surveys are conducted using standard methods (Traynor et al. 1990; Williamson and Traynor 1984) using calibrated echosounders at 18, 38, 70, 120 and 200 kHz. Abundance will be estimated for forage species not routinely enumerated during acoustic surveys; abundance of euphausiids, myctophids and capelin (O2.17) will be measured from estimates of acoustic backscattering (S_A; defined in MacLennan et al. 2002), also applying noise-correction for 120 and 200 kHz (Watkins and Brierley 1996) and frequency-differencing to separate euphausiids (Stanton et al. 1996; Miyashita 1997; McKelvey and Wilson 2006) from other important scatterers (Gauthier and Horne 2004a,b) and will be ground-truthed with targeted trawl hauls (Aleutian wing, Methot and Tucker trawls) (e.g., Honkalehto et al. 2002). Stomach samples will be collected during these surveys and compared to the prey field to measure the functional foraging response of fish predators (O2.16). A single acoustic frequency (38 kHz) will be added to the surface trawl survey (O2.28), thereby allowing for the estimation of pelagic species abundance in the middle and inner domains so that the acoustic and surface trawl surveys cover the entire Bering Sea shelf. The timing of the surface trawl survey will encompass movement by forage species and young-of-the-year walleye pollock into the inner front. In addition, spatial patterns of groundfish and shellfish will be determined from the standard NOAA bottom trawl survey (O2.25, Fig. 3), which provides a lengthy time series (standard since 1982) on the focal species of pollock, cod and arrowtooth flounder.

We will simultaneously sample ocean habitat conditions during forage species, groundfish and shellfish surveys during summer and on commercial fishing vessels during summer and winter in order to understand the relation between pollock, euphausiids, myctophid and capelin distributions and ocean habitat (O2.17). We will add underway nitrate and oxygen sensors – indicators of frontal structure, phytoplankton, nutrients and production - to the acoustic survey aboard RV *Oscar Dyson* and underway seawater temperature, salinity, nitrate, oxygen and chlorophyll sensors to one of the two contract fishing vessels used in the bottom trawl survey, thus creating an underway sampling capability of seawater temperature, salinity, dissolved nitrate, chlorophyll fluorescence and dissolved oxygen measurements. Water samples will be taken for salinity, nitrate, chlorophyll and oxygen calibration and processed in the laboratory ashore. We will outfit the two contract fishing vessels used in the bottom trawl survey with CTDs on their trawl head ropes to obtain vertical profiles of temperature and salinity during the summer bottom trawl survey as well as the fall and winter pollock fisheries. We also will outfit the RV *Oscar Dyson* with expendable bathythermographs (XBTs) to increase the density of vertical profiles during the acoustic survey (O2.26). Products will include time series, maps and data files for scientific interpretation and input to physical oceanographic models.

This project component will synthesize historical information on the spatial distribution of pollock and cod (including egg and larval distribution), euphausiids, water column profiles, sea ice distribution, surface and sub-surface temperature and light levels to describe the ocean habitat requirements of pollock and cod and identify hot spots for predators that consume pollock and euphausiids (O2.19). Data sources are bottom trawl surveys, acoustic surveys, commercial fisheries acoustic data and commercial catch. Spatial associations will be assessed using spatial general additive models (GAM) (Ciannelli et al. 2004a). Project O2.19 complements NPRB project #709 "Species-habitat associations in three flatfish species of the eastern Bering Sea as mediated by demographic, human and cross-scale environmental forcing" which considers yellowfin sole, Alaska plaice and arrowtooth flounder; together these two projects will synthesize pollock, cod and arrowtooth flounder spatial distributions and ocean habitat information.

Pollock, Cod and Arrowtooth Flounder (Age-0 and 1) Production: The successful recruitment of fish larvae to juvenile nursery areas is a necessary condition for growth, energy storage and subsequent survival. Climate effects on meteorological and oceanographic conditions impact transport pathways and thus fish production that upper trophic levels depend on. This project will examine spatial distribution, abundance and larval transport effects on fish production through research cruises providing data a spatial ecosystem model (M.47); the model is described in Section D.6.

Larval (Pacific cod, walleye pollock, arrowtooth flounder), age-0 (walleye pollock, Pacific cod), and age-1 juveniles (walleye pollock) will be collected on four research cruises per year, 2008-2010. Seasonal coverage leverages three existing NOAA surveys, spring ichthyoplankton (North Pacific Climate Regimes and Ecosystem Productivity (NPCREP), May, O2.7), acoustic (MACE, June-July, O2.26) and surface trawl (BASIS, August-September, O2.23) surveys. It also incorporates a funded BEST cruise for physical oceanography (July, O1.2). Vertically stratified tows will receive higher priority in 2008 and 2009 than 2010. The first cruise of the seasonal cycle (May) will collect physical (SeaCat) data, larval fish prey (CalVET and bongo nets), and ichthyoplankton (bongo vertically integrated tows, MOCNESS or Multinet® vertically stratified tows and neuston tows) samples. In addition, satellite-tracked drifters will be deployed to follow patches with high concentrations of target fish larvae. Conclusive identification of arrowtooth flounder (A. stomias) eggs and larvae is currently impossible in the Bering Sea due to the co-occurrence of a near-identical congeneric (A. evermanni). We propose developing a DNA-based method that will unequivocally identify arrowtooth flounder eggs and larvae at sea. A PCR-RFLP protocol will provide real-time capability to ensure accurate assessment of A. stomais larval/egg numbers.

Data from the drifters deployed in May would be used to construct the survey grid for the second cruise (July). The BEST component of the project will collect physical and chemical information. The NPRB component staged on this cruise will collect zoo- and ichthyoplankton (MOCNESS or MultiNet® vertically stratified) samples (O2.7). The third cruise (BASIS surface trawl survey, August/September) will collect physical profiles, nutrients, chlorophyll, zooplankton (CalVet and/or bongo net), ichthyoplankton and juvenile fish (large surface trawl) samples, especially age-0 pollock, Pacific cod and other non-gadoid forage fish. Acoustics and midwater trawl samples will be used to estimate abundances of age-0 pollock, Pacific cod and other forage species (O2.23, O2.28). In 2009 and 2010, a fourth cruise, the acoustic survey (O2.26), will evaluate survival of age-1 pollock. For example, the three age-0 fish cruises will track the progression of the 2008 year class during 2008, while the 2009 acoustic survey will evaluate the survival of this year class. In 2009 and 2010, the bottom trawl survey (O2.25) will measure relative abundance of age-1 Pacific cod and age-1 arrowtooth flounder, but since these small fish typically pass through the net, absolute abundance and thus survival can not be evaluated. Larval fish and meso-zooplankton and micro-zooplankton prey collections will be identified at the University of Alaska or at the Polish Plankton Sorting and Identification Center (ZSIOP), then verified in Seattle. Results from these cruises will provide much-needed information on distribution and abundance of target fish species, the physical environment (temperature, salinity), and larval growth to be used in ensuing bioenergetics models (O2.24).

The cod and arrowtooth flounder ichthyoplankton component will not be as comprehensive as the pollock component. Pacific cod eggs are semi-demersal and not routinely collected in ichthyoplankton tows, so we will not be able to provide data on Pacific cod egg abundance and distribution. Pacific cod larvae are planktonic, and are commonly collected in ichthyoplankton tows, often co-occurring with walleye pollock larvae, so we will be able to provide vertical and horizontal distribution and abundance estimates for Pacific cod larvae. The costs and shiptime required for a comprehensive survey of age-0 arrowtooth flounder in late autumn is beyond the scope and resources of this project. However, NPCREP is currently planning very small-scale studies of newly settled flatfishes on the eastern Bering Sea (EBS) shelf in 2008 and 2010. If these studies are implemented, data would be added to the information available for a more complete synthesis of arrowtooth flounder early life stages in the EBS in collaboration with Ciannelli et al. (O2.19). Likewise, if NPCREP were to conduct a winter ichthyoplankton cruise (February) in any of the field years, efforts would be made to obtain complementary data on overwintered (age-1) fish (pollock, Pacific cod) in collaboration with Hollowed et al. (O2.17) and Heintz (O2.24).

Condition, energy content and allocation between lipid and protein in juvenile fishes vary seasonally and reflect predictable changes in prey availability (Bucheister et al. 2006). Typically, lipid stores reach a maximum in late fall (Vollenweider et al. in press), just as prey availability begins decreasing. In young-of-the-year, energy supplies fall to their minimum values during metamorphosis from larval to juvenile stages (Gatten et al. 1983), which must be quickly replenished to prepare for their first winter, yet has rarely been documented. We will examine the condition and energy dynamics of juvenile pollock, cod and arrowtooth flounder (O2.24), thus testing the critical size for winter survival hypothesis and data for maps of energy distribution in spatial predator/prey models. We will determine the caloric content and percent protein and lipid of pollock, cod and arrowtooth flounder samples collected during the seasonal (2-4 annually, depending on species) research cruises using modern analytic chemistry methods (e.g., Vollenweider et al. in press). It is recognized that measuring the lipid content and energy density of the other key forage species, such as euphausiids, capelin and myctophids, will ultimately be necessary for assessing their condition, fitness and quality as prey for fish, seabirds and marine mammals. Results from this study will be used to identify and design those measurements and analyses.

Retrospective Analysis of Patterns in Fish, Seabird and Marine Mammal Productivity: The retrospective analysis (O3.30) will analyze time series of productivity measures of selected fish, seabird and marine mammal species in relation to measures of climate variability in the eastern Bering Sea. The main goals are to quantify variability in productivity of the focal species (walleye pollock, cod, arrowtooth flounder, common and thick-billed murre, black-legged kittiwakes, fur seals), to quantify interactions among these species, to describe and quantify potential effects of climate variability on their productivity and to identify potential effects of climate forcing on the strength and direction of interactions among species. Measures of productivity examined will include recruitment, condition indices and biomass for major commercial groundfish and shellfish species (O2.25), forage species and shrimp biomass corrected for consumption by major predators (Aydin et al. 2006), summer zooplankton abundances (Napp and Shiga 2006), reproductive success for three focal seabird species (Dragoo et al. 2003), fur seal pup production (Towell et al. 2006) and environmental data on sea ice extent, sea surface and bottom temperature, wind speed and direction and other climate indices (http://www.beringclimate.noaa.gov/).

The analysis of available productivity time series will focus on: 1) covariation among productivity, abundance, or biomass trends of different species, 2) climate effects on the productivity of selected species and 3) interactions among species and effects of climate on these interactions. Most of these time series span over 30 years and demonstrate substantial variation in annual productivity and climate, thus providing the data contrast needed to inform parameter estimation and to detect relationships. We will examine patterns of covariation among time series to identify species or species groups that show similar or opposite patterns of variability in these series following the approach of Mueter et al. 2006. To identify potential bottom-up effects on the focal species, we will quantify relationships between climate variables and measures of productivity, including testing for potential non-linear relationships (Hastie and Tibshirani 1990; Wood 2000) and identification of new hypotheses regarding the effects of climate variability on productivity. To minimize the chance of identifying spurious relationships (Type I error), we will use retrospective analyses to test a series of *a priori* hypotheses and evaluate whether a given hypothesis is supported by the available data (Mueter et al. 2006). We will use GAMs to allow for non-linear effects, such as dome-shaped, sigmoidal or threshold effects.

Seasonal Distribution and Foraging Ecology of Seabirds and Baleen Whales: Baleen whales consume large quantities of plankton and fish and are not tied to a central place to raise their young. In contrast, seabirds are central place foragers when breeding with relatively high consumption to biomass ratios (Ciannelli et al. 2004b; Hunt et al. 2000). This project will compare the two groups of endothermic predators and their prey. The cetacean component will use at-sea visual surveys (O4.38). The seabird component will use at-colony measures of reproductive success and diets (O4.37), at-sea telemetry of breeding birds (O4.35) and at-sea visual surveys and diet sampling (O4.36, Fig. 6). At-sea locations of cetaceans and seabirds will be compared to forage species abundance and distribution from standard acoustics surveys (O2.26, O2.28), including analysis of how hot spot persistence affects foraging location (O4.40) and energy content of potential prey fields (O2.24). This will be the first attempt to follow two major groups of apex foragers simultaneously, in relation to their prey base, in Alaskan waters.

Trained observers onboard research vessels will conduct standard visual line-transect surveys for cetaceans (O4.38, Buckland et al. 2001, 2004; Moore et al. 2002) and visual strip-transect surveys for seabirds (O4.36, Gould and Forsell 1989) with adaptations to improve density estimates (see Hyrenbach et al. 2001; Spear et al. 2004) and population trends (Clark et al. 2003). Cetacean abundance estimates are expected to have coefficient of variations (cv) of 0.3 (fin whales) and 0.5 (humpback whales) (Moore et al. 2002). Seabird abundance estimates are expected to have coefficient of variations (cv) of 0.15 (kittiwakes) and 0.25 (murres) (Nielson et al. 2003). The surveys will continue NPRB-funded coverage of NOAA and NSF cruises (Fig. 6) during winter, spring and summer.

Seabirds nesting at St. Paul are thought to be influenced by ice-edge productivity to the north, whereas seabirds at St. George depend on foraging conditions to the south near the shelf edge (Byrd et al. in press). Seabirds from these two representative colonies will be used to study diet (through chick prey sampling), foraging location, trip duration and frequency of breeding common murres, thick-billed murres and black-legged kittiwakes during 2008-2010 through use of data loggers (O4.35). Each year 30 breeding birds of each species at each site will be monitored from June through August with a tag attached to each bird's back by means of cyanoacrylate glue or Tesa tape and cable ties (Benvenuti et al. 1998; Irons 1998; Daunt et al. 2002). Sample sizes were chosen to obtain a representative sample of foraging behaviors within each colony, year and sex (Anderson et al. 2005; Lyons et al. 2005). In addition, data on seabird reproductive parameters (nest initiation rate, clutch size, hatching success, fledgling success, reproductive success, brood reduction and growth rates), indicators of foraging conditions for breeding birds (adult body condition and stable isotope ratios) and colony size will be collected by standard methods (Williams et al. 2002) during ongoing USFWS seabird monitoring program enhanced with additional data not routinely collected on diet and body condition (O4.37).

Seabird and cetacean foraging locations from at-sea visual surveys and at-sea telemetry will be analyzed in relation to oceanographic data and prey type and abundance data (O2.26) to support detailed predictive models of seabird and cetacean distribution and relative abundance versus prey distribution and oceanographic variables (Redfern et al. 2006). In addition, we will quantify the distributions of pelagic forage fish, i.e., the existence of prey hot spots, whether these hot spots persisted across years and the location of apex predators relative to hot spot persistence based on apex predator frequency of association with persistent hot spots (O4.40, Gende and Sigler 2006).

Patch Dynamics Study (O4.62): Patches are formally defined as significant spatial variations in oceanic biomass, but are more broadly recognized to reflect significant spatial variation in any feature of prey that is important from the perspective of the predator for exploitation of the resource. Prey patches may occur at scales of less than 1 m to several kilometers with persistence times of minutes to months. They are also known to vary in species composition, biomass, energy content of prey, and distribution (size of patch, density within a patch, density of patches, and distance from colony/rookery). However, it is not yet known how apex predators respond to variability in prey patches (patch dynamics) and the consequence it has on population dynamics of top-predators in the Bering Sea.

This study component is a coordinated fine-scale study of birds and mammals, and their forage base to determine the consequences of spatial patterns (i.e., patches) on predator-prey dynamics. Concurrent field studies will be undertaken during 2008, 2009 and 2010 in two geographic areas of the Eastern Bering Sea (St. Lawrence Island from March – May, and at the Pribilof Islands during July and August). The Pribilof Islands region includes a comparison between seabirds and fur seals at St. Paul and St. George islands. Seabirds (thick-billed murres and black-legged kittiwakes) and marine mammals (northern fur seals and Pacific walrus) will be tracked at sea to determine where, when, and how they capture prey. Forage species will be sampled from vessels using nets, bottom grabs, and hydro-acoustics to describe the patches (quality and quantity) and their relationship with physical oceanography. Relative densities of prey patches and foraging success of birds and mammals will be related to regional and interannual differences in population processes. Specifically, we will examine (*i*) how changes in patch dynamics influence diets (species composition and energy content), (*ii*) how diets affect nutritional status of individuals, which in turn determines population dynamics (reproductive success and population trends).

D.6 Linked Modeling (Potential)

BSIERP integrated modeling will extend predictive capabilities for lower trophic level, forage species, fish, seabird and marine mammal production and spatial distribution. Specifically these models will predict spatial distributions of forage fields, local impacts on predators including fishermen and fishery value. Additional modeling projects will address fisheries management method improvement and uncertainty characterization.

We will estimate these quantities by expanding a conceptual model of the ecosystem to include life history characteristics and spatial variation, and by constructing a range of alternative system models (often referred to as "operating models") based on the conceptual model, as recommended by Marasco et al. (2007). The range of alternative system models is broad enough to ensure that a plausible suite of hypotheses regarding ecosystem processes are represented and tested.

- Potential models are listed in Table 1, as well as products (Table 2) and hypotheses addressed (Table 3).
- Additional modeling projects characterize uncertainty and examine fisheries management method improvement (Blended forecasts/management strategy evaluation (M.55), and Management strategy resilience (M.50)).

The next three sections are organized to describe a vertically-integrated set of models, competing models and management, uncertainty and prediction.

A. Vertically-integrated models

A set of vertically-integrated set of models will link climate, physical oceanography, lower trophic level, upper trophic level and economic outcomes. The set consists of climate downscaling (M.3), spatial ocean (ROMS) (M.4), lower trophic level (NPZ) (M.5), forage and euphausiid dynamics (M.47), and economic and spatial fishing predictions (M.48, M.49) models (Table 3, Fig. 1).[1] Vertically-integrated models offer three advantages.

- Vertical linkage allows two-way coupling between ecosystem components, which provides feedback between components rather than one-way coupling. For example, the forage and euphausiid dynamics model (M.47) will be implemented within the spatial ocean (ROMS)-lower trophic level (NPZ) model (M.4, M.5). Implementing two-way coupling is critical as these zooplankton and forage species exhibit strong feedback between components, both top-down and bottom-up (Aydin et al. 2006) and zooplankton abundance has decreased in recent years (Napp and Shiga 2006).
- Vertical linkage will allow us to forecast economic effects for fisheries contingent on Intergovernmental Panel on Climate Change (IPCC) climate scenarios (e.g. increased operating costs for pollock vessels due to ocean warming effects on the southeast Bering Sea pollock population).
- Modeling multiple IPCC climate scenarios within the vertically integrated set will allow us to depict uncertainty in these economic forecasts. (Other sources of uncertainty also will be incorporated; e.g. interannual variation in pollock production.)

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[1] The first three models (climate downscaling, spatial ocean, lower trophic level) have been recommended for funding through NSF. The remaining models are potential models described for consideration by the NPRB Ecosystem Modeling Committee for funding by NPRB.

B. Competing Models

A set of competing models will examine an array of mutually exclusive ideas of how physical and biological processes interact to predict the quantities of interest (Table 3). These ideas can't all be right, and our system of models provides a systematic means of finding the right ideas by comparing prediction to observation. The competing models challenge the vertically-integrated models, both in predictive ability and in necessary complexity. The competing models are a behavioral foraging model (M.54) and a biomass dynamics model (M.61) (Table 3). The modeling project Blended forecasts/management strategy evaluation (M.55) also has competing model elements.

C. Management, uncertainty and prediction

A formal Management Strategy Evaluation (MSE) will address management decision-making and uncertainty in model projects Blended forecasts/management strategy evaluation (M.55) and Management strategy resilience (M.50).

EMC question *(k). How will the probabilistic nature of model forecasts be represented in model output, and how will this be communicated to eventual users of the model predictions?*

The probabilistic nature of model forecasts will be represented by relative probability density functions and cumulative distribution functions. Density functions will be compared between models, to explore the consequences of admitting additional uncertainty. Model predictions also will be compared in a blended forecast similar to that produced by the Intergovernmental Panel on Climate Change (IPCC) (M.55).

The probabilistic nature of model forecasts will be communicated using novel indicators of direct relevance to stakeholders (e.g. NPRB/PICES workshop; Kruse et al. 2006). For example, uncertainty can be shown as frequencies of poor catch generated through Monte Carlo simulations; a 20-year "drought" of reduced pollock catch could be expected to occur much more often in high fishing than in low fishing scenarios (Fig. 7). Indicators will be expressed in relative (percent change due to policy or long-term climate) rather than absolute terms (expected returns).

The remainder of questions/criteria composed by the EMC differ from model to model based on implementation, and are described in the more detailed descriptions below.

DETAILED MODEL DESCRIPTIONS

The following EMC questions are covered differently for each model, within the model descriptions below:

a. What is the model intended to predict?
f. What data are available (temporal and spatial resolution, time span covered, data quality) to drive, calibrate, and test the model?
g. How will the existing data be used to quantify model fit and predictive power?
h. What pertinent future data are anticipated to become available within the time frame of the project?
i. How will the future data be used to quantify model fit and predictive power?
j. How has it been determined that the proposed quantity and quality of data can be expected to be sufficient for the intended use in tuning and testing the model?

A. Vertically-integrated models

ROMS and Climate Downscaling (NSF; Nick Bond, Al Hermann, PIs, M.3, M.4): A unified set of circulation and biological models based on the Regional Ocean Modeling System (ROMS) will be used for high resolution, spatially-explicit downscaling of climate projections through the food chain to fisheries. For the core modeling work, we will utilize a subset of the archived Intergovernmental Panel on Climate Change (IPCC) models to provide scenarios of climate patterns. These scenarios will be downscaled to 10-km (entire Bering Sea) and 3-km (Southeastern Bering Sea) circulation and hydrographic fields using ROMS, with embedded, spatially explicit biological and economic models (NPZ (M.5), FEAST (M.47), and economic (M.48, M.49)). These will be used for ensemble runs of the coupled biophysical system, to predict future states and their uncertainty. We will also develop a simplified, "rapid deployment" version of the circulation model, to facilitate the initial exploration of hypotheses and for use in field studies. Numerical details can be found in Haidvogel et al. (2000), Moore et al. (2004) and Shchepetkin and McWilliams (2004). For downscaling of climate scenarios, we will implement a suite of ROMS-based regional-scale and local-scale circulation models, linked via one-way coupling, that focus on the Bering Sea. A similar set of downscaling models based on ROMS has already been developed for the Northeast Pacific (including the Bering Sea) under GLOBEC support (Curchitser et al, 2005). Our approach can simultaneously accommodate both tidal and subtidal information, such that the internal forecast/hindcast includes both subtidal and tidal dynamics. Boundary conditions for the outermost grids are obtained from global hindcast and forecast simulations; e.g. the Community Climate Modeling System (CCSM) at NCAR. This approach will be extended under the present proposal to include forcing and boundary conditions from an ensemble of different atmospheric and oceanic products from the various IPCC climate forecasts.

ROMS-NPZ (NSF; Georgina Gibson, PI, M.5): A Nutrient-Phytoplankton-Zooplankton-Detritus (NPZ-D), lower trophic level ecosystem model coupled to a three-dimensional ROMS physical model of the Bering Sea will be used to explore relationships between zooplankton production and water temperature, sea-ice retreat, and wind driven mixing. The coupled NPZ-ROMS model will thus provide valuable information towards understanding how climate driven variability in important physical phenomenon i.e. water temperature or sea ice retreat, can affect recruitment success of planktivorous fish. This model will include specific estimates of benthic secondary production for eventual coupling with benthic modeling (e.g. crabs, flatfish, and cod). This foresight could be used by fisheries managers to assist in the development of a sustainable approach to resource utilization

FEAST- Forage/Euphausiid Abundance in Space and Time (Kerim Aydin, Al Hermann, Anne Hollowed, Brian Fadely, Mike Dalton, PIs, M.47): The flow of energy through forage fish is poorly understood; however, evidence suggests that the competition of forage fish for food, particularly for euphausiids, may be a key structural element to understanding upper trophic level variation in the Bering Sea (Napp; Aydin et al. 2006) and the connection between components at this level may be extremely tightly (Aydin and Mueter in press). ROMS accommodates the addition of biologically active state variables; these have served as a convenient point of departure for the creation of new biological models. We will implement a spatially explicit forage fish/pollock model based within ROMS, which communicates directly with the NPZ model and allows for behaviors such as aggregation at fronts. This approach allows for depletion of primary and secondary production by all higher trophic levels, hence a simultaneous treatment of both top-down and bottom-up effects in the ensemble runs with euphausiids and pollock as the key interface between controlling mechanisms. The scale of 10km with 2km nested resolution for hotspots is critical to understanding foraging responses along fronts and for central-place foragers, and indices of prey patchiness will be developed from field data to examine finer scales of foraging. The FEAST model will have several sub-components, developed separately and finally integrated: ***Forage species component*:** FEAST will model pollock with age structure, size structure, and bioenergetics applied to track both abundance, growth, and condition as state variables in each grid cell of the model. **Key corroboration and tuning** for this model will be provided from the bioenergetics modeling and fieldwork (O2.24). Other forage species (capelin, eulachon, sand lance, myctophids, squid, shrimp) abundances will be included from multi-frequency differencing of acoustic surveys (O2.17) and functional foraging responses measured on these surveys (O2.16). These latter species will be modeled using gradient movement and prey search rules, calibrated against field data. ***Cod/ATF/Salmon component:*** Pacific cod, arrowtooth flounder, and Pacific salmon are important predators of forage in the Bering Sea. Predation fields will be modeled from these species based on the functional foraging response component of this project (O2.16), and scenarios of changing predator biomass will be incorporated into management evaluations. *Bird/mammal component*: the specific bird and mammal foraging retrospective analyses and fieldwork (O3.30, O4.35-40) will be used to predict bird and mammal foraging success based on the forage fields produced by FEAST, and the direct measurements of bird and mammal diets will be used to calibrate/corroborate FEAST predictions of forage fields during the study years. ***Economic component*:** Dynamic economic model components for pollock and cod will be implemented directly within the ecosystem model to provide a 2-way coupling that links fishing effort to abundance of target species. This coupling will be used to simulate rates of fishing mortality, a critical feedback. This economic component will be implemented as a set of decision rules that depend on ex-vessel prices, input costs, stock dynamics, regulations, and climate. Catchability coefficients and other parameters in the decision rules will be estimated from logbook data and biological surveys. Trends in global prices for seafood, fuel, and other inputs will be based on the IPCC (SRES) climate scenarios. These dynamic models will link variables that measure abundance or concentration of target species to fishing effort, and simultaneously, determine the feedback rates of fishing mortality for the corresponding ecological model. Estimates of catch and landings from the integrated economic-ecological models will be used to assess impacts of climate change on individual ports and sectors using a regional economic model for Alaska. An emphasis will be placed on externalities specific to modeled carbon emission scenarios; for example, in relation to rising fuel costs in the future.

Spatial Economic Models for Pollock and Cod (Alan Haynie, PI, M.48, M.49): Fishery managers directly regulate people, and thus, only indirectly manage fish stocks. Thus, from a fishery management perspective, an analytical framework for evaluating how fishermen may respond to future environmental conditions is critical to forecasting the future status of managed stocks. Moreover, environmental changes will almost certainly be accompanied by changes in input prices, technology, and regulatory systems that may be reasonably expected to influence the magnitude and distribution of benefits across sectors within a fishery, and among communities that support those sectors. The proposed research will help managers evaluate how fishermen will respond to changes in spatial abundance of fish populations, and to evaluate the economic impacts to fish processors and communities. The proposed research methodology will use dynamic and spatially explicit economic models of the fleets that target pollock and cod. These economic models will be linked to, or embedded in, biological (i.e. single-stock) and ecosystem models (M.47) coupled with the ROMS oceanographic model (M.4, M.5). Economic effects of the IPCC (SRES) climate change scenario used to drive ROMS will be evaluated according to each fleet's simulated response to changes in the spatial and temporal distribution of its target species. To avoid a biased view of the economic effects, the aim is to model the entire fleet of vessels that target pollock and cod, not just the subset of large vessels with observers, which will require translating some archived logbook data. The proposed research will use the economic models, in conjunction with the biological/ecosystem models, to simulate how fleets may respond under alternative forms of fishery management to determine which forms are best suited to forestall stock declines, improve stock recovery, or minimize variability in the catch.

The spatial fishing choice models to be developed in this project are both retrospective and predictive in nature. Smith (2002) and Branch et al. (2005) discuss a number of alternative models that may be used for such an analysis, but for the task of predicting the costs and benefits of changes in spatial fishing distribution, discrete choice models such as those that will be used in this project have proven to be the most useful. The proposed work in this area builds upon a significant body of literature (e.g. Haynie and Layton (2004), Haynie (2005), Smith and Wilen (2003), Smith (2005), Branch et al. (2006)). Standard measures of discrete choice models will be used to evaluate fit and predictive accuracy, namely pseudo-R-squared and mean-squared error (MSE). In addition to standard measures of model-fit, model averaging of results will be employed to incorporate uncertainty about future conditions (see Haynie (2005) for a description of this methodology). The pollock model will distinguish among seven oceanographic domains, for which the survey data have already been disaggregated. The model for cod will include intra-annual migration between summer feeding grounds and winter spawning grounds, and will link changes in the spatial distribution of fishing effort to changes in environmental characteristics, such as wind speed and anticipated changes in stock location. Logbook and other data will be used to identify the factors that significantly influence fisher location choice. Spatial and temporal distribution of effort by vessels targeting pollock and cod are required for model estimation and testing to provide an empirical basis for making predictions about how fishing may shift under climate change scenarios; existing data will be compiled and analyzed as part of this modeling project. Spatial choices will be simulated under different climate scenarios and shifts in fish stocks.

B. Competing models

EMC question d. What alternative models (other mechanisms, greater degrees of spatial and temporal aggregation, simple statistical predictors) are plausible competitors whose performance should be tested against the model being developed?

Behavioral Foraging Model (Marc Mangel, PI, M.54): We propose to model the energy flow from forage fish to piscivorous fish, murres, kittiwakes and fur seals by bringing key aspects of behavioral ecology (predator foraging behavior) into population dynamics in order to make sense of the community ecology (e.g., Mangel and Wolf 2006). The "profitability" (energy content divided by handling time) of specific forage fish and the encounter rate will determine whether an item is included in the diet of the predator trying to maximize its rate of energy return (Clark and Mangel 2000). Piscivorous fish are wide ranging but birds and seals are generally central place foragers; therefore their diet breadths will differ. We will use the oceanographic data (O1.1, O1.2, O2.17) and lower trophic level model predictions (M.5) to formulate the foraging rules for the predators. The behavioral rules then determine predation and resulting predator population growth in an iterative manner. For patchily distributed prey resources, foragers may starve even if the mean rate of intake is sufficiently high. Therefore, we propose a state variable model that tracks a measure of gut content, reserves or time since last meal, through the use of stochastic dynamic programming (Clark and Mangel 2000). This will allow us to build a thorough description of functional responses and characterize production and mortality in the predator populations.

Correlative Biomass Dynamics Model (Gordon Kruse and Franz Mueter, PIs, M.61): We will use a multispecies biomass dynamics model (Collie and DeLong 1999) to examine interactions among species (e.g., competition and predation) that show evidence of covariation. We will include species based on the results of the correlation and multivariate analyses (O3.30) and life-history characteristics. We will extend the Collie and DeLong (1999) model to shared climate effects on productivity and on predator-prey or competitive interactions among groups. For example, the model may include a gadid group, a shelf flatfish group and a crab group, with an ice or temperature variable that affects the productivity of cod and flatfishes in opposite ways, or include interaction terms that vary with climate. Fitting to existing biomass indices and fisheries history will retrospectively assess if and how climate variability has affected the interactions among species. These novel models provide a useful intermediate step between statistical models of climate-productivity relationships and complex multispecies age-structured models or ecosystem models.

C. Management, uncertainty and prediction

EMC QUESTIONS ADDRESSED HERE:

b. What specific aspect of the prediction is anticipated to be of direct value for fisheries management?

c. What measure of "accuracy" in the prediction is crucial to determining the usability of that prediction to fisheries management?
e. How will the achieved predictive power of the model be compared against the performance of plausible alternatives, and how will this guide subsequent choices about model form and parameterization?

Specific MSE component I: Competitive existing models for blended forecasts, and management strategy evaluation (Andre Punt, Kerim Aydin, PIs, M.55): We will evaluate a set of models currently available for the Bering Sea: (a) Single species-assessments w/ correlative recruitment indices (e.g. Ianelli et al. 2006; Wilderbuer et al. 2002); and (b) MSVPA and MSM (Jurado-Molina et al. 2005). Additionally, we will examine autocorrelative biomass dynamics/network models (Gaichas, 2006) and nonlinear correlative models (Hsieh et al. 2005) as "null" models for testing the added value of more mechanistic approaches. This set covers a range of model "types" from among models available to project PIs. We will provide analyses of model strengths, weaknesses, and uncertainties using blended model and Bayesian averaging techniques, and test management strategies against long-term predictions in a management strategy evaluation (MSE) framework. Such a thorough analysis of competing models for the same ecosystem will provide value to Bering Sea management efforts and future modeling advice for other ecosystems. This application of MSE will consider management strategies in a broader context than has been the case in the past and will specifically attempt to implement the guidelines of Marasco et al. (2007) as regards evaluating management strategies in an ecosystem context. The work will be performed by a Postdoctoral Associate working with Andre Punt at the University of Washington for four years, to produce blended model averages from the multiple models and perform MSE analyses on identified alternatives. To this end, the project includes funding two workshops in 2009 and 2011 for the modelers to bring results together, and for working with relevant managers/researchers to identify and implement strategies for testing.

Specific MSE component II: Management Resilience Study (Keith Criddle, PI, M.50): To address the question of what type of governance may be best suited to forestall stock declines, improve stock recovery, or maintain more consistent yields, we propose to use stochastic-dynamic simulation models. We will explore the stability, magnitude, and distribution of benefits and costs under share-based and alternative resource management regimes in response to environmentally forced variations in the abundance and distribution of target stocks (as predicted by M.47) and in response to substantive changes in input and product markets. We will combine models of alternative fishery governance regimes (Greenberg and Herrmann 1994; Natcher et al. 1996; Herrmann et al. 1998; Criddle et al. 2001; Herrmann and Criddle 2006) with integrated bioeconomic models of climate forced variation (Criddle et al. 1998; Criddle and Herrmann in press) to create spatially differentiated multi-sector stochastic dynamic models. The robustness of the model will be investigated through sensitivity analyses and stochastic simulations.

The proposed work will model pollock (and potentially king and Tanner crab, depending on funding options) because these fisheries are among the most economically important in the Bering Sea region and because these fisheries have been managed under a variety of management structures. While the crab species are not extensively evaluated elsewhere in BSIERP, they provide a potentially valuable source of information about the economic and social impacts of major changes in management structure. Moreover, there are clear indications that the productivity of pollock populations is affected by climate variation (Criddle et al. 1998) and that the distribution of pollock stocks is shifted northward and westward under warm water conditions. Similarly, there are strong indications that crab recruitment is governed by abiotic factors and that climate variation may lead to changes in the relative productivity and profitability of southern and northern stocks. In this project, we will combine elements of our previous successful models to create spatially differentiated multi-sector stochastic dynamic models formulated to allow us to explore the resilience of alternative management regimes in response to variations in the magnitude and distribution of economic benefits under environmentally forced variations in the abundance and distribution of target stocks and in response to substantive changes in input and product markets.

Specifically, this project will explore the sustainability and resilience of the shore-based, at-sea, and CDQ sectors of the pollock fishery and Aleutian Islands, Bristol Bay, Pribilof Islands, and Norton Sound stock of king and Tanner crab. The models will be used to assess the effects of environmental variation, the effect of variation in input and output prices, the role of management actions, and the resiliency of alternative governance regimes. The robustness of the model will be investigated through sensitivity analyses and stochastic simulations.

While we will rely on models developed in other components of the BSIERP to characterize biological responses to environmental variation, we are prepared to develop approximate structural-time series models (e.g. Criddle and Havenner 1991, Criddle and Herrmann 2007) if the multispecies and ecosystem models are unable to provide values needed to parameterize our simulation models. We will obtain estimates of key input prices, output prices, and operating costs, and relate parameter estimates to changes in environmental, regulatory, and governance systems. The stock dynamics functions and price and cost estimates will be combined in discrete-time bioeconomic models. Because of the uncertainty inherent in the specification and estimation of the bioeconomic models, we will conduct a sensitivity analysis of model performance with respect to the value of the estimated coefficients. The sensitivity analysis will establish confidence limits on the model predictions and highlight relationships that require more detailed analysis. Once we have established confidence limits for the bioeconomic simulation model, we will be able to parameterize forcing factors and explore the probable bioeconomic impacts of environmental variation, variation in input and output prices, management actions, and the resiliency of alternative governance regimes.

Logistics

l. What is the schedule for providing NPRB with specified data files of observations and model output fields, and how does this set of observations and outputs ensure transparency and verifiability?

See Table 4.

D.7 Local and Traditional Knowledge

The local and traditional knowledge (LTK) component of the BSIERP has four objectives:

1. Document, characterize, and quantify local harvest practices and changes thereto in order to better understand the relationship between Bering Sea communities and the Bering Sea ecosystem (harvest surveys, key informant interviews, group discussions);
2. Document and characterize local understanding of Bering Sea ecosystem function to allow comparison with biological understanding and sharing of knowledge between both ways of knowing (key informant interviews, group discussions);
3. Integrate the results of (1) and (2) across the communities involved, identifying key similarities and differences as well as regional trends or associations with particular environmental features (collaborative analysis;
4. Incorporate the results of (1), (2), and (3) into ecosystem models and other syntheses developed through BSIERP.

These objectives will be carried out by a team of researchers, including community members, using standard survey and ethnographic methods (e.g., household harvest surveys, harvest calendars, key informant interviews, focus group discussions, etc.). A regional advisory board of about ten members of the overall research group (five community researchers, five others) will guide the overall project, making sure that research in the different communities is consistent and promoting cross-community interaction and comparison. In each community, a local advisory board will help make sure that the research proceeds smoothly and in accordance with community expectations and interests.

The communities tentatively identified are Akutan, St. Paul, Togiak, Emmonak, and Savoonga. The locations of the communities create a rough transect north-south and also in relation to sea ice. All have a history of research on LTK and/or subsistence harvest surveys, providing useful information and a basis for identifying trends and changes over spans of a decade or more.

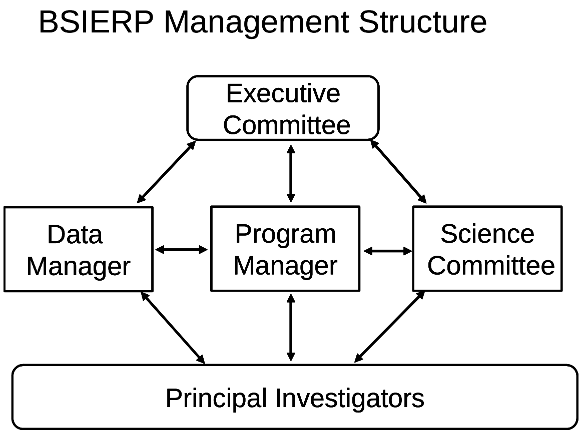
D.8 Research Products

Each BSIERP project will provide specific products (Table 3). These products will be of sufficient quality to appear in the peer reviewed scientific literature and in high profile management scenario evaluation documents to be provided to regulatory authorities, such as the NPFMC and Alaska Board of Fisheries Secretaries of Commerce and Interior and supporting agencies (NMFS, USFWS, ADFG) and resource management workshops.

E. Program Management, Timeline and Milestones

Program Management: A coherent management structure is necessary for the success of an interdisciplinary, multi-faceted ecosystem research program.

Executive Committee: Ultimate responsibility for program management resides in the Executive Committee (Sigler [chair], Byrd, Stabeno, Trites, Whitledge). In addition, we request that a NPRB representative serve on the Executive Committee.



Program and Data Managers: Daily operations will be the direct responsibility of the Program Manager (NPRB) and the Data Manager (Coyle), both whom report to the Executive Committee. The Program Manager is the hub of information on all aspects of the program, having the authority to obtain information directly from the Principal Investigators. The Program Manager works directly with the Science Committee (see next paragraph), which is the organizing body for the Principal Investigators. The Data Manager works with the Science Committee to implement the data management plan and keeps the Program Manager advised. The Principal Investigators will work with the Data Manager and Science Committee to ensure smooth and efficient exchange of information within the program, and the Program Manager will facilitate communication of information by working closely with the NPRB Outreach Manager. Because funding will be supplied by two different organizations, NSF and NPRB, the Program Manager also will develop processes to ensure that all operations meet or exceed the program management requirements of both funding organizations. The Program Manager will facilitate use of material resources, such as research vessels that are controlled by various agencies, by helping scientists conform to the differing requirements for participation imposed by the owners of the resources.

Science Committee: Individual researchers are integrated into larger, discipline-oriented science projects, each with a team leader who coordinates individual project activities. The Science Committee is composed of the team leaders and is the primary body for overseeing field programs, ongoing scientific planning, data exchange, and synthesis of results. Team leaders are listed in section 3, contact information.

Research Platforms: Listed here are cruises with the platform and funding source listed in parenthesis, assuming both the NOAA ships *Oscar Dyson* and *Miller Freeman* are available after 2008. Spring zoo-/ichthyoplankton (O2.7, *Miller Freeman*, NOAA – NPCREP); summer zoo-/ichthyoplankton (O1.2, proposed, NSF), bottom trawl (O2.25, chartered fishing vessels, AFSC), acoustic (O2.26, *Oscar Dyson*, AFSC), and surface trawl (O2.23, chartered fishing vessels, AFSC). All AFSC-funded cruises are standard agency surveys except for the 2009 acoustic survey. The standard acoustic survey is conducted biennially (scheduled 2008 and 2010). NOAA is adding the 2009 acoustic survey solely to support BSIERP, which constitutes a substantial in-kind contribution by NOAA.

BSIERP also will employ satellites and moorings as observational platforms. The moorings are described in an earlier section. Full seasonal satellite coverage in the BSIERP study area will be provided through collaboration with Professor Sei-Ichi Saitoh of Hokkaido University. The satellite coverage will occur through JAXA sponsored projects at Hokkaido University and bio-optical calibrations will occur on T/S Oshoro Maru annual mid-summer cruises. Hokkaido University has made annual investigations of the eastern Bering Sea with the T/S *Oshoro Maru* during the summer for many years. Hokkaido University presently plans to continue the T/S *Oshoro Maru* cruises to the Bering and Chukchi Seas during the International Polar Years of 2007 and 2008. In addition, the BSIERP ship sampling plans during the spring, summer and fall seasons will provide additional bio-optical calibration data for interpretation of the satellite data. Together, the collaboration will benefit both Japanese and BSIERP investigators.

Timeline: See Tables 3 and 4.

Deliverables: Deliverables include semi-annual reports (due January 15 and July 15 each year) and the final project report. In addition, brief written reports to the modeling group will summarize quantitative results that are of potential relevance to the modelers. Peer reviewed, scientific publications will follow the completion of each research component. We anticipate at least 40 scientific publications. In addition, we will report these products in the Ecosystems Chapter of the Stock Assessment and Fishery Evaluation (SAFE) report for the Bering Sea and Aleutian Islands. These products also will be reported in the Ecosystems Considerations sections of several Bering Sea fish stock assessments (SAFE). This substantial new information will reduce the uncertainty of ecosystem considerations when recommending single-species fish catch quotas and managing seabird and marine mammal species, some of which are declining in abundance.

Dissemination: Research results will be disseminated to local Bering Sea communities, at management meetings, including the North Pacific Fishery Management Council, at the annual Marine Science in Alaska symposium, various national and international scientific meetings, including Alaska and national American Fisheries Society (AFS) meetings and North Pacific Marine Science Organization (PICES) meetings and in leading fisheries journals.

Graduate Students and Post-docs: We propose to include 2 M.Sc., 7 Ph.D. and 9 post-docs in our study. Durations are M.Sc. (2 years), Ph.D. (4-5 years) and post-doc (2-4 years), with full-time support.

F. Data Management Plan

Two great challenges facing large research programs are management and analysis of large, diverse data sets generated by numerous investigators from various institutions and backgrounds. The BSIERP study will generate vast amounts of data from retrospective, laboratory, field and modeling research. These data require quality control, careful documentation through metadata and media storage and protocols that allow researchers quick and easy data access. Without a strong data management program, data access and analysis can be inconsistent, material lost, researchers unaware of data availability, access and analysis platforms, resulting in long delays between data acquisition and dissemination. To address these challenges, the data manager will adopt and modify data management software developed for storage, access and imaging of another large ecosystem study (BASIS [Bering Aleutian Salmon International Survey] data set) for the BSIERP study, provide researchers with standard analysis and graphics applications for communicating scientific results and work with the Alaska Ocean Observing System (AOOS, http://www.aoos.org) to provide easy data access for BSIERP researchers and the general public. The data manager will provide some BSIERP data in near-real time to the Alaska Ocean Observing System and ensure that all data collected is archived with NPRB. The Arctic Region Supercomputing Center (ARSC) will provide 760,000 computer hours for model computations (more as needed), unlimited storage capacity for model output and help with data access software development and implementation as part of the ARCS commitment to support research underway at University of Alaska (see attached support letter).

Data policies: Data use will follow guidelines established by the U.S. GLOBEC Data Policy (GLOBEC Report No. 10, February 1994), existing OPP data policies and proposed SEARCH policies. NSF and NPRB will clarify specifications of the exact protocol. All data submitted to BSIERP will be required to have accompanying metadata compliant with FGDC standards. Metadata and data will be transferred to NPRB within two years after each field season.

G. Outreach and Education Plan

To be developed by NPRB Outreach Manager.

H. Coordination Strategy

Our coordination strategy has been to engage as many of the top researchers in the Bering Sea as the budget limitations of the BSIERP and the matching contributions from leading research institutions would permit. BSIERP has therefore been designed to operate in a highly integrated fashion with existing monitoring and process-based studies conducted by NOAA and USFWS (Table 1, Fig. 1), including standard fisheries surveys and colony-based seabird and fur seal studies. BSIERP brings $14.7M in matching funds from NOAA and USFWS, which includes the agency activities relevant to the BSIERP. We also plan to apply results from relevant NSF funded projects (Section D.5). Coordination of existing and proposed projects will occur as a routine part of project management (Section E). In addition, our PIs are involved to some extent in research for nearly all of the significant funding sources in the Bering Sea, including the Minerals Management Service North Aleutian Basin studies and the research of the Pollock Conservation Cooperative. Community involvement is part of this strategy and is described in the community outreach and LTK project sections (Sections D.7 and G). Investigators from proposed and existing research components will collaborate toward a common end, working side by side during field operations and modeling efforts and serving together on BSIERP's Science Committee.

I. Figures and Tables

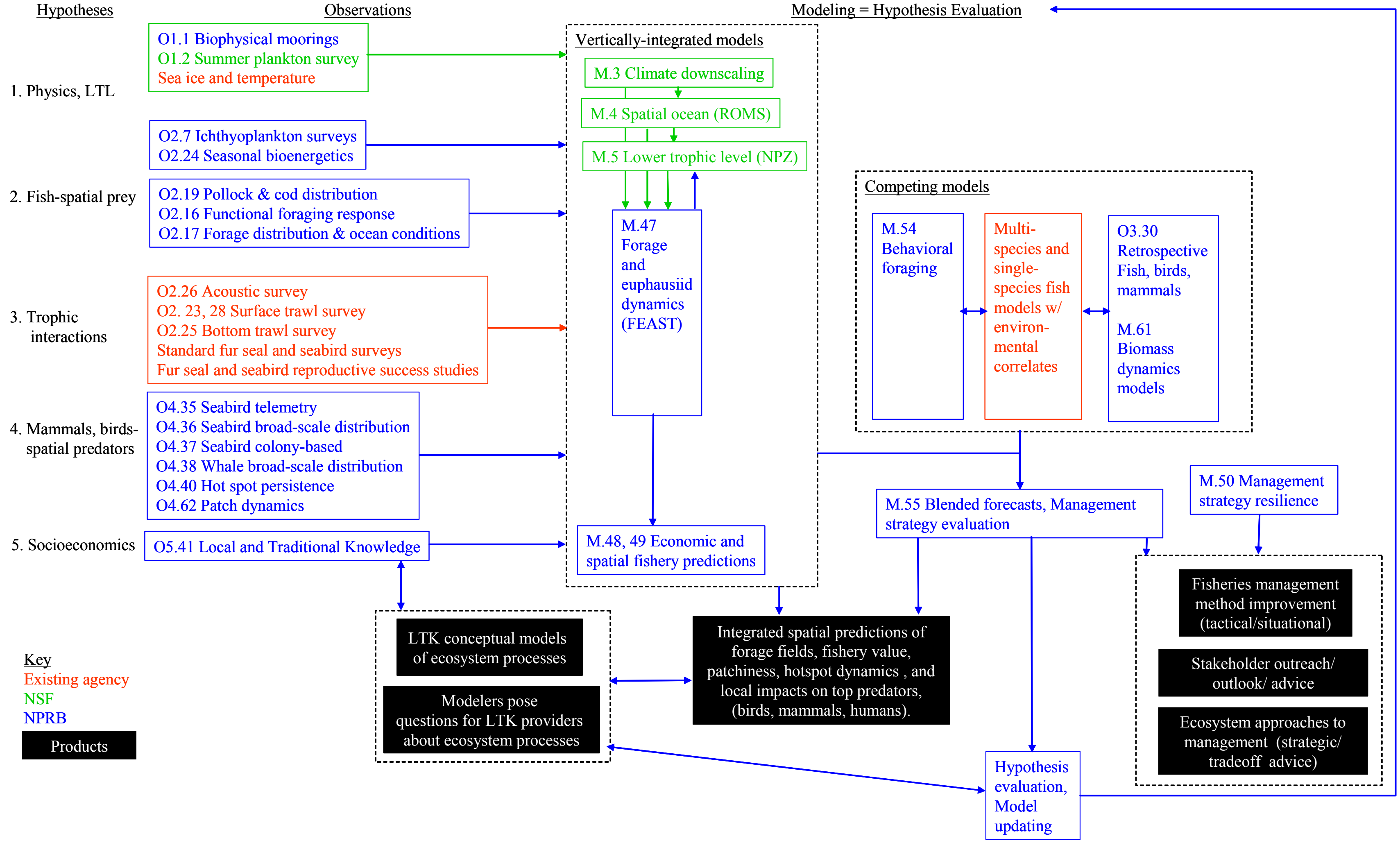


Fig. 1. All project components are connected, with research products from field projects and retrospective analyses (‘O’ prefix, e.g., O1.1) providing inputs to a suite of physical, biological, ecosystem and socioeconomics models (‘M’ prefix, e.g., M.3); these models in turn are linked together and provide scenarios and advice for management of subsistence and commercial fisheries. Field studies are located to the left and models to the right; horizontal arrows show the flow of data from field studies to models; vertical arrows show the links between models; models that are adjacent are competing models. Project links to hypotheses also are shown in Table 2. **(Potential models are shown.)**

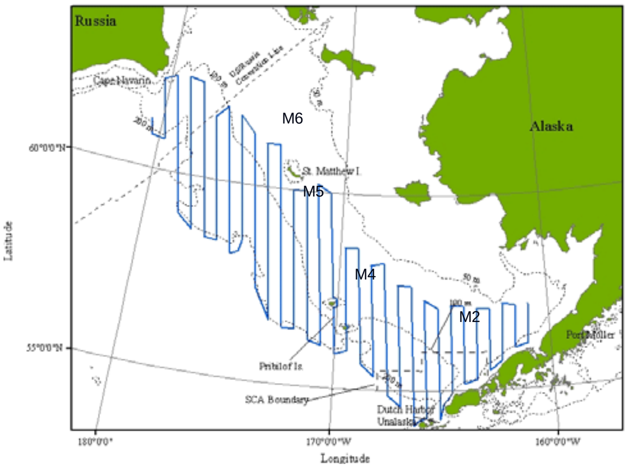


Fig. 2. Acoustic survey (O2.26) transects and 4 biophysical mooring (O1.1) locations (M).

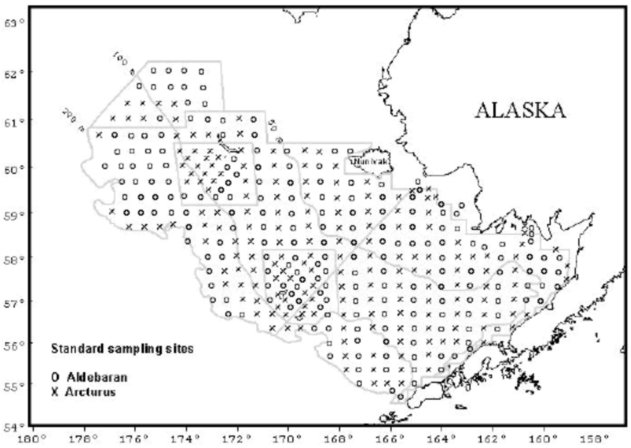


Fig. 3. Bottom trawl survey (O2.25) locations.

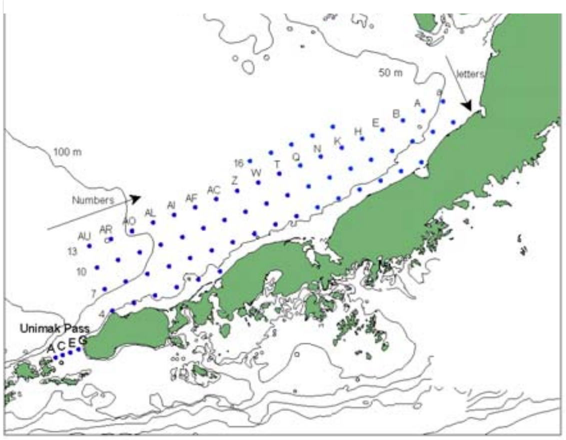


Figure 1. NOAA Bering Sea ichthyoplankton survey map. Springtime sampling in May of each field year.

Fig. 4. Ichthyoplankton (O2.7, May NPCREP) survey locations.

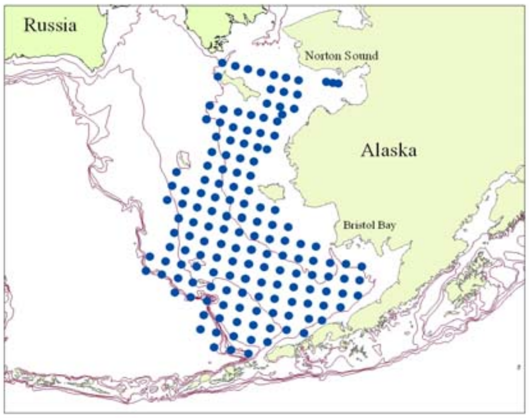


Fig. 5. Surface trawl survey (O2.23, BASIS) locations.

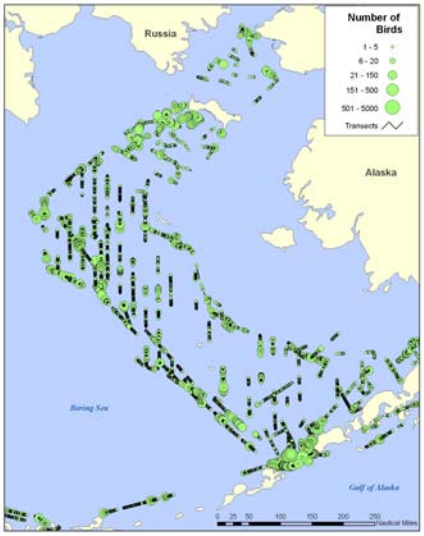


Fig. 6. At-sea seabird visual survey (O4.36) data.

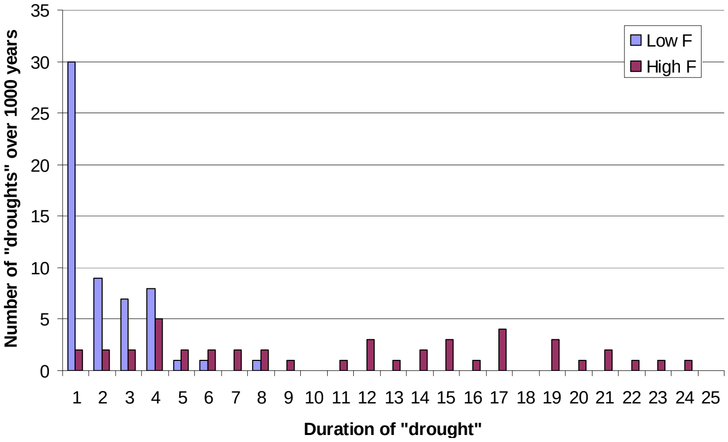


Figure 8. Frequency distributions showing duration catch remained below a reference level ("drought") for low and high rates of fishing (F).

Table 1. Project list.

Project	Project Components	Label	Principal Investigators	NPRB ($)	In-kind ($)
Lower trophic level	Biophysical moorings (4)	O1.1	Stabeno, Whitledge, Napp	$ 732,259	$ 1,707,106
Ichthyoplankton	Ichthyoplankton surveys	O2.7	Hillgruber, Duffy-Anderson, Napp, Matarese, Eisner	$ 1,068,052	$ 1,245,612
	Seasonal bioenergetics	O2.24	Heintz	$ 250,000	$ 373,400
Fish	Acoustic survey	O2.26	Wilson	$ 154,499	$ 2,349,000
	Surface trawl survey	O2.23	Farley	$ -	$ 1,516,200
	Surface trawl survey acoustics	O2.28	Horne, Parker-Stetter, Farley	$ 425,731	$ -
	Bottom trawl survey (epi-benthic)	O2.25	Lauth	$ -	$ 3,240,000
	Pollock & cod distribution	O2.19	Ciannelli, Bailey	$ 332,313	$ -
	Functional foraging response	O2.16	Aydin, Farley	$ 258,260	$ 23,040
	Forage distribution & ocean conditions	O2.17	Hollowed, Wilson, Kotwicki, DeRobertis, Ressler, Cokelet	$ 567,123	$ 553,311
Trophic interactions	Fish, birds & mammals	O3.30	Mueter, Kruse	$ 286,913	$ -
	Hot spot persistence	O4.40	Sigler, Kuletz, Wilson	$ -	$ 55,200
Seabirds	Seabird telemetry	O4.35	Irons, Byrd, Roby	$ 600,000	$ 303,000
	Seabird broad-scale distribution	O4.36	Kuletz	$ 550,438	$ 555,000
	Seabird colony-based	O4.37	Byrd	$ 350,000	$ 1,179,000
Patch	Patch Dynamics	O4.62	Trites, Jay, Grebmeier, Benoit-Byrd, Heppell, Sampson, Irons, Byrd, Roby, Kytasky, Kuletz	$ 2,300,000	
Marine mammals	Whale broad-scale distribution	O4.38	Friday, Moore, Zerbini, Clapham	$ 300,000	$ -
	Fur Seal colony-based		Ream	$ -	$ -
Local and Traditional Knowledge	Local & traditional knowledge	O5.41	Sepez, Hunn, Huntington, Langdon, Zavadil, Fall	$ 1,000,000	$ 49,190
Modeling			to be determined	$ 2,500,000	
	potential		***potential***		
	Forage euphausiid (FEAST)	M.47	Aydin		
	Behavioral foraging	M.54	Mangel		
	Biomass dynamics	M.61	Mueter, Kruse		
	Integrate economic-ecological	M.48	Dalton, Aydin, Haynie		
	Spatial fishery choices	M.49	Haynie		
	Management strategy resilience	M.50	Criddle, Valcic, Greenberg		
	Blended forecasts, Management strategy evaluation	M.55	Punt		
Education and Outreach			Deans (NPRB)	$ 100,000	
Data Management	Data Management		Coyle	$ 800,000	
Program Management			NPRB	$ 600,000	
Total				**$ 13,175,588**	**$ 13,149,059**

Table 2. Project links to hypotheses.

Projects	**Label**	1a	1b	1c	2a	2b	2c	2d	2e	3a	3b	3c	4a	4b	5a	5b	5c
Biophysical moorings (4)	O1.1	■	■														
Summer plankton survey	O1.2		■														
Ichthyoplankton	O2.7, O2.24		■	■			■	■									
Fish	O2.26, O2.23, O2.28, O2.25, O2.19, O2.16, O2.17		■	■	■	■		■	■								
Trophic interactions	O3.30					■	■	■	■	■		■	■				
Seabirds	O4.35, O4.36, O4.37									■	■	■	■	■			
Patch dynamics	O4.62									■	■	■	■	■			
Marine mammals	O4.38									■	■	■	■	■			
Local and Traditional Knowledge	O5.41, O5.42	■	■	■	■	■	■	■	■	■	■	■	■	■		■	
Lower trophic level modeling	M.3, M.4, M.5	■	■														
Forage euphausiid (FEAST)	M.47			■	■	■	■	■	■	■	■	■	■	■			
Behavioral foraging	M.54									■			■				
Biomass dynamics	M.61									■		■					
Economic-ecological spatial	M.48, M.49														■	■	
Management strategy resilience	M.50																■
Blended forecasts, Management strategy evaluation	M.55																■

Table 3. Research products and timelines provided by BSIERP.

									Year			Month											
Project	**Project Components**	**Label**	**Products**	**Water column**	**Surface only**	**Point sample**	**Transect**	**Sample spacing (km)**	**2008**	**2009**	**2010**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Lower trophic level	Biophysical moorings (4)	O1.1	Temperature, salinity, flourescence	▨		▨		~260	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Summer plankton survey	O1.2	Phytoplankton & zooplankton abundance and rates																				
Ichthyoplankton	Ichthyoplankton surveys	O2.7	Pollock, cod and arrowtooth flounder ichthyoplankton seasonal abundance	▨		▨			▨	▨	▨					▨		▨					
	Seasonal bioenergetics	O2.24	Pollock, cod and arrowtooth flounder seasonal energy content						▨	▨	▨					▨	▨	▨	▨	▨			
Fish	Acoustic survey	O2.26	Pollock abundance and spatial distribution	▨			▨	37	▨	▨	▨						▨	▨					
	Surface trawl survey	O2.23	Juvenile pollock spatial distribution		▨	▨		~56	▨	▨	▨								▨	▨			
			Temperature, salinity, flourescence, light		▨		▨		▨	▨	▨								▨	▨			
			Temperature, salinity, flourescence, nutrients, oxygen, light, turbidity, phytoplankton, zooplankton	▨		▨			▨	▨	▨								▨	▨			
	Surface trawl survey acoustics	O2.28	Pollock abundance and spatial distribution	▨			▨		▨	▨	▨								▨	▨			
	Bottom trawl survey (epi-benthic)	O2.25	Pollock, cod and arrowtooth flounder abundance and spatial distribution			▨		37	▨	▨	▨						▨	▨					
	Pollock & cod distribution	O2.19	Spatial distributions of spawning pollock and cod and their eggs and larvae (retrospective)																				
	Functional foraging response	O2.16	Pollock, cod and arrowtooth flounder diet composition						▨	▨	▨						▨	▨					
	Forage distribution & ocean conditions	O2.17	Temperature and salinity	▨		▨			▨	▨	▨		▨	▨			▨	▨		▨	▨		
			Temperature, salinity, flourescence, nitrate, and oxygen		▨		▨		▨	▨	▨						▨	▨					
			Euphausiid, myctophid and capelin abundance and spatial distribution	▨			▨		▨	▨	▨						▨	▨					
Trophic interactions	Fish, birds & mammals	O3.30	Environmental influences and trophic interactions for seabirds, marine mammals, and groundfish and shellfish (retrospective)																				
	Hot spot persistence	O4.40	Seabird and cetacean foraging response to prey persistence						▨	▨	▨						▨	▨					
Seabirds	Seabird telemetry	O4.35	Colony-based seabird distribution, diet						▨	▨	▨							▨	▨				
	Seabird broad-scale distribution	O4.36	Seabird spatial distribution, diet		▨		▨		▨	▨	▨						▨	▨					
	Seabird colony-based	O4.37	Seabird reproductive success, diet						▨	▨	▨							▨	▨				
Patch dynamics	Patch dynamics	O4.62	Fur seal, murre, kittiwake, walrus and their prey, fine-scale spatial distribution	▨	▨		▨		▨	▨								▨	▨				
Marine mammals	Whale broad-scale distribution	O4.38	Humpback and fin whale spatial distribution		▨		▨		▨		▨						▨	▨					
Local and Traditional Knowledge	Local & traditional knowledge	O5.41	Ethnographic interviews, subsistence surveys, community view of ecosystem																				
Modeling	Climate downscaling	M.3	Integrated spatial predictions of forage fields, fishery value, patchiness, hotspot dynamics , and local impacts on top predators, (birds, mammals, humans)																				
	Spatial ocean (ROMS)	M.4																					
	Lower trophic level (NPZ)	M.5																					
	Forage euphausiid (FEAST)	M.47																					
	Behavioral foraging	M.54																					
	Biomass dynamics	M.61																					
	Integrate economic-ecological	M.48																					
	Spatial fishery choices	M.49																					
	Management strategy resilience	M.50																					
	Blended forecasts, Management strategy evaluation	M.55																					
Data Management	Data Management		Study database																				
Program Management	Program Management		Periodic status reports																				

Table 4. The proposed timeline for research reporting by quarter is summarized below. Highlighted cells denote quarters when activities occur, x's denote specific deliverables to be completed by the end of the indicated quarter as described below. The schedules for some research activities are generalized; for example, seasonal bioenergetics (O2.24) samples are collected during several surveys (e.g., Spring ichthyoplankton survey) and analyzed in the laboratory (Laboratory analysis activity). Semi-annual reports are due January 15 and July 15 each year.

		2007				2008				2009				2010				2011				2012			
Research activity or project		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Initial planning meeting				■																					
Annual meeting						■				■				■				■				■			
Laboratory analyses									■	■	■	■	■	■	■	■	■	■							
Data analyses									■	■	■	■	■	■	■	■	■	■	■						
Modeling & retrospective analyses						■	■	■	■	■	■	■	■	■	■	■	■	■	■						
Field data to models										■				■				■							
Model outputs to fieldwork planning									■				■												
Preparation of manuscripts													■	■ x	■	■	■	■ x	■	■	■	■ x			
Synthesis																		■	■	■	■	■	■	▒ x	
Semi-annual reports						■ x		▒ x		■ x		▒ x		■ x		▒ x		■ x		▒ x		■ x			
Final report																								▒ x	

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5. Budget Information and Budget Narratives: See attached.

6. Resumes: See attached.

7. Current and Pending Support: See attached.

8. Letters of Support: See attached.

9. Local and Traditional Knowledge: See Section D.7 of the BSIERP Research Plan.

10. Other Information: MOUs among institutions or letters of collaboration will be written as necessary if our proposal is funded by NPRB.

Permits will be obtained as necessary if our proposal is funded by NPRB. In general, this requirement will be met through future permits anticipated for NOAA and USFWS research.

Graduate Students and Post-docs within BSIERP are described in section E. of the BSIERP Research Plan.