Retrospective analysis of patterns in productivity of fish, seabirds, and marine mammals in the eastern Bering Sea ecosystem

Contact Information

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Summary

The productivity of upper trophic level species in the eastern Bering Sea varies in response to climate variability and human forcing, although the relative contribution of these drivers and the underlying mechanisms remain poorly understood. This retrospective analysis will (1) quantify past patterns of variability and covariation among time series of productivity of selected fish, seabird, and marine mammal species; (2) test whether historical patterns and trends in these series are consistent with existing hypotheses; (3) suggest new hypotheses based on relationships among the productivity of different ecosystem components and relationships between their productivity and observed climate variability; and (4) provide functional forms and parameter estimates (and their uncertainty) that link the productivity of different ecosystem components to climate variability. The analysis will utilize existing data on productivity, including measures of recruitment, survival, and growth or condition, of major upper trophic level species. Results will contribute to the overall research program in two important ways. First, results will directly support the proposed modeling projects by providing parameters linking the productivity of individual species to climate variability, which is essential for predicting the effects of future climate variability. Second, identified relationships between climate and productivity can be incorporated into existing stock assessment models.

This project is one component of the Bering Sea Integrated Ecosystem Research Program (BSIERP). The integrated program hypotheses and projects are listed in Tables 1 and 2.

Species and Geographic Scope

This project examines walleye pollock, Pacific cod, arrowtooth flounder, rock sole, yellowfin sole, snow crab, red king crab, common and thick-billed murre, black-legged and red-legged kittiwakes, fur seals, and forage fish (juvenile walleye pollock and capelin) in the Southeastern Bering Sea.

Hypotheses

This project addresses BSIERP hypotheses 1a-c, 2c, 2e, 3a, and 4a (Table 2)). A detailed list of specific, testable hypotheses is provided below.

Project Description

In this study, available time series of productivity, abundance, and/or biomass for the species listed above will be analyzed in an integrative, rather than single-species, analysis and will include several steps focusing on

1. Covariation among productivity, abundance, or biomass trends of different species. This will be an extension of previous covariation studies in the Bering Sea ecosystem to include seabirds and mammals, as well as several groups of forage species.
2. A comprehensive examination of potential climate effects (temperature, ice cover and retreat, advection, wind mixing, and stratification) on the productivity of selected species and species groups, including (a) empirical tests of existing hypotheses on the productivity of and on interactions among upper trophic level species, and (b) functional relationships and estimates of parameters (and their uncertainty) that link the productivity of upper trophic level species to climate variability.

The analysis of covariation and climate effects will be based on already existing time series, which will be compiled as needed to include the most recent year available at the time of analysis. Data sources include:

- Indices of productivity for the major commercial fish species that are easily available or can be computed from available data. These include recruitment, survival rates adjusted for the effect of spawner abundance (stock-recruit residuals), and weight-at-length anomalies (condition index) for commercial fish species. Annual estimates of recruitment and biomass of commercial fish species will be obtained from NMFS stock assessments. Individual weight and length measurements for these species will be obtained for all years where data are available from the NMFS bottom trawl survey database. Recruitment and biomass estimates are available on an annual basis since at least the late 1970s for all of the commercial groundfish species. Individual length and weight data for computing condition indices are available for a variable number of years since 1975 and annually since 1999 for walleye pollock, Pacific cod, arrowtooth flounder, flathead sole, and yellowfin sole.
- Recruitment and stock-recruit residuals for crab populations will be based on estimates of recruitment and biomass from NMFS and ADF&G crab stock assessments in collaboration with ADF&G crab stock assessment scientist Jie Zheng. No annual index of condition or growth for crab is available, but decadal periods of faster or slower growth (shifts in molting probabilities) can be estimated by length-based population assessment models.
- No measures of productivity for forage fishes and shrimp are currently available but we will obtain annual biomass estimates for these species based on catch rates in annual Bering Sea bottom trawl surveys (starting in 1982), which may be corrected for consumption by major predators (Aydin et al. 2006).
- Zooplankton productivity has been estimated for few years and locations in the eastern Bering Sea (Ken Coyle, UAF, pers. comm.), but annual time series of summer zooplankton abundances (Napp and Shiga 2006, Mike Palmer, pers. comm.) may be included in the analysis as a proxy for prey availability from 1954 to present (some missing years).
- Annual estimates of productivity (fledging success) for the four focal seabird species will be obtained from colony-based studies (Dragoo et al. 2006, Vernon Byrd, pers. comm.). Estimates are available since 1975, although murres were not surveyed in all years.
- Annual or biennial estimates of fur seal abundance (counts) and productivity (reproductive success as measured by total estimated pup production, and pup condition) at St. George and St. Paul island will be obtained from the patch dynamics component (O4.62) and from the National Marine Mammal Laboratory.
- Environmental data on sea ice thickness and extent, bottom water temperatures, wind speeds at St. Paul Island, and model-based estimates of SST and winds will be compiled from various data sources (NOAA and NWS online data sources, bottom temperature from RACE division, AFSC, Seattle). Indices of stratification and bloom timing on the shelf will be updated based on data from the biophysical moorings (O1.1).
- Additional data sets or derived indices that will be used in the analysis are described below under specific hypotheses.

The analytical approach and tentative candidate hypotheses to be examined are detailed below:

1. Previous retrospective studies of covariation in the Bering Sea have typically focused on commercially important fish species with long time series of productivity and abundance (e.g. Mueter et al. 2007). The proposed analyses will include seabirds and mammals, as well as several groups of forage species, to compare patterns of variability and trends among commercial and non-commercial species and among species from several trophic levels. The goal of the covariation analysis is to identify important relationships among these different groups of species that will help us understand

and quantify potential interactions. Quantifying such interactions may have direct management applications (Reid et al. 2005, Roth et al. in press) and is critical to the ecological models of BSIERP. Following the approach in Mueter et al. (2007), we will examine patterns of covariation among indicator series (time series of productivity, abundance, or biomass) to identify species or species groups that show similar or opposite patterns of variability in these indicators.

2. Understanding past variability in productivity in relation to water temperature, ice conditions, wind mixing, advection, and other measures of climate variability is essential to predicting the potential effects of future climate scenarios on fish, seabird, and marine mammal productivity. In particular, the functional relationships identified in our study can be used to project the future status of key components and interactions in the Bering Sea ecosystem using climate forecasts from Intergovernmental Panel on Climate Change (IPCC) model outputs.

    To identify potential bottom-up effects on the focal species we will quantify and test for significant relationships between climate variables and measures of productivity. These analyses will include exploratory analyses as well as tests of *a priori* hypotheses, which are described below. Exploratory analyses will consist of simple correlations between measures of productivity and environmental variables (adjusted for autocorrelation or trends in the data) to test for potential linear relationships. In addition, we will use scatter plots and simple non-parametric regressions (smoothers) of productivity on environmental variables to test for potential non-linear relationships (Hastie and Tibshirani 1990, Wood 2006). These analyses will help identify new hypotheses regarding the effects of climate variability on productivity. Moreover, the non-parametric regressions will provide estimates of the magnitude of any such effects. However, because of the number of variables and hypotheses examined, these analyses will carry a high risk of identifying spurious relationships (Type I error).

    To minimize the chance of such errors, we will use retrospective analyses to test a series of *a priori* hypotheses relating the productivity of selected upper trophic level species to environmental variables and / or to the abundance or biomass of lower trophic level species. We will follow the hypothesis testing approach outlined in Mueter et al. (2006) to evaluate whether a given hypothesis is supported by the available data. Hypotheses will be tested in a generalized statistical modeling framework and we will pay particular attention to the form that these relationships may take (e.g., linear, dome-shaped, threshold, etc.) and to potential differences in observed responses among cold and warm periods. The latter is critical to understanding how climate-productivity relationships may change in response to a warming climate. For each hypothesis, we will construct two or more statistical models that are biologically plausible. The most parsimonious model will be selected to estimate the form magnitude of hypothesized effects and assess their statistical significance. Most hypotheses postulate effects on one or more of the focal species and were developed based on previous research and in discussions with other researchers. They may be further refined or modified to make best use of information provided by other components (pollock & cod distribution, O2.19; forage distribution & ocean conditions, O2.17; seabirds, O4.35-37; patch dynamics, O4.62) and to avoid overlap.

    Our tentative hypotheses focus on the effects of climate variability on Pacific cod, flatfishes, crab, seabird, and fur seal productivity, as well as on the abundance of forage species. Available data series on productivity (as indexed by recruitment and spawner-to-recruit survival for most fish species, abundance trends for forage fishes, fledging success and breeding phenology for seabirds, and pup production for fur seals) and additional indices as described below will be used to test the following, previously untested hypotheses:

    - <u>Pacific cod</u>: Spawner-to-recruit survival rate (adjusted for spawner abundance, i.e. stock-recruit residuals) and subsequent recruitment is higher when ice retreats early or no ice is present during the larval phase (H1a). This effect is hypothesized to be masked (weaker or non-existent) during period of high predator abundance in accordance with the OCH. A threshold model (low/high biomass) or a multiple regression with interaction between predator biomass and timing of ice retreat will be used to test the hypothesis. An index of total predation pressure will be constructed based on the summed mid-year biomass of major predators of larval cod and their diet composition.

- Pacific cod: Survival rates and recruitment are reduced when spring storms delay the onset of the summer, non ice-associated bloom. To test the hypothesis we will use the estimated bloom date from Mueter et al. (2006), who provided empirical evidence that pollock survival is reduced during years with a delayed bloom. A similar hypothesis (match-mismatch) is being examined by an ongoing NPRB project (NPRB project number 605; Benjamin Laurel, AFSC, pers. comm.). This project will also provide satellite-based estimates of the onset of the spring bloom (1997-2005), which will be compared to our bloom date estimates for verification.
- Pacific cod: Survival rates and recruitment are reduced if wind mixing is low and insolation (SST) is high during the larval phase (H1b). Larval survival is hypothesized to increase with increasing wind mixing (increased nutrient supply to surface layer) and may level off or decrease at high levels of mixing (decreased foraging success because of turbulence) akin to the optimal environmental window proposed to regulate recruitment of pelagic fishes in upwelling regions (Cury and Roy 1989). Average summer (Jun-Sep) SST and average summer wind mixing will be used as explanatory variables.
- Pacific cod: The combined effects of timing of ice retreat, onset of the summer bloom, and summer SST and wind mixing during the larval phase will affect survival and recruitment of Pacific cod as postulated in the previous three hypotheses.
- Flatfish: Improved survival of flatfish during years with onshore advection (Wilderbuer et al. 2002) results from the physical separation of juveniles from outer domain piscivores, which reduces predation pressure on juvenile flatfish (H1c). To explicitly test this hypothesis we will construct spatial maps and indices of average "predation potential" for the inner (< 50m), middle (50-100 m), and outer (100-180 m) domains, based on the abundance of major flatfish predators in trawl survey samples and their estimated consumption of juvenile flatfish. Consumption will be estimated based on average diet composition and ration estimates (Aydin et al. 2006). Under the hypothesis, predation pressure is postulated to be higher in the outer and middle domains.
- Flatfish: The predation potential on juvenile flatfish is higher, and survival of flatfish is lower, in warm years with low summer winds because the inner front is weakened, and therefore predators will move into the inner domain (H2c). To test this hypothesis we will (i) test for significant effects of temperature and wind on the average predation potential and (ii) model flatfish survival as a function of predation potential and indices of larval transport (which will interact to determine flatfish survival because larval transport determines the supply of larvae to the inner domain, while predation potential determines their survival).
- Gadids and flatfish: The condition (weight at given length) of small-mouth flatfish (rock sole and yellowfin sole, which rely on benthic prey), is higher during cold periods with a late ice retreat because of increased energy flow to the benthos and benthic productivity (H2e). Conversely, the condition of walleye pollock, which rely primarily on pelagic prey, is lower during such periods. Condition will also be affected by the total abundance of flatfish or pollock due to density-dependent effects. To test these hypotheses we will model condition as a function of both timing of ice retreat and total abundance.
- Snow crab: The survival and recruitment of snow crab is larger during years with an extensive cold pool. Previous analyses have shown that the abundance and distribution of snow crab is related to the cold pool extent (Mueter and Litzow in review, Orensanz et al. 2004). Changes in

local abundance may result from changes in distribution or changes in survival and recruitment. Here, we extend the previous analyses to model effects of the size of the cold pool on snow crab survival and subsequent recruitment. Because it is not clear whether the hypothesized effects of warmer temperatures act on larval or later stages, effects will be examined at multiple lags. In a complementary ongoing NPRB study, an individual-based modeling approach is being used to examine the role of advection on survival of larval snow crabs (NPRB project number 624; Sarah Hinckley, AFSC, pers. comm.).

- Red king crab: Survival of red king crab larvae is enhanced when winds are light and the water column is stable during the late spring/early summer larval period. Zheng and Kruse (2000) speculated that such conditions favored the predominance of *Thalassiosira* diatoms in the spring bloom; *Thalassiosira* are preferred prey of red king crab larvae, which must feed within 2-6 days of hatching or they starve (Paul and Paul 1980). In a five-year study in Auke Bay, Alaska, phytoplankton community composition is strongly influenced by short-term weather (Bienfang and Ziemann 1995); *Thalassiosira* are minor constituents of the spring bloom in windy years when the water column is well mixed. To test this hypothesis, we will examine wind stress during the pelagic larval period (May-June) during years of strong and weak recruitment to determine whether conditions favorable to *Thalassiosira* blooms (stable water column) are associated with years of strong year classes of crabs.
- Fur seals and seabirds: The reproductive success of fur seals, murres, and kittiwakes and condition of fur seal pups in the Pribilof Islands is positively related to the abundance of lipid-rich fish such as capelin, herring, and sandlance (see H3a). To test the hypothesis we will use bottom trawl survey data to develop indices of capelin and herring biomass within a pre-defined area around the Pribilof Islands corresponding to the approximate foraging ranges of fur seals (Call et al. in press, Robson et al. 2004), murres, and kittiwakes. In addition, the local abundance of capelin around the Pribilofs is hypothesized to be lower in years with reduced sea ice and higher temperatures (H4a). We will test the hypothesis by regressing the capelin biomass index on average summer SST around the Pribilof Islands.
- Fur seals and seabirds: The reproductive success of fur seals, murres, and kittiwakes and condition of fur seal pups in the Pribilof Islands is lower during years with a high abundance of piscivorous fish because of competition for prey (H3a). To test the hypothesis we will construct a trawl survey-based index of abundance for large piscivorous fish (pollock, cod, arrowtooth flounder) that occur in significant numbers within the feeding ranges of the seabirds and fur seals.
- Seabirds: The reproductive success of seabirds is higher if the breeding phenology of murres and kittiwakes matches the timing of the summer phytoplankton bloom on the middle shelf. We will use a model-based index of bloom timing (Mueter et al. 2006) to examine the time of hatching in these seabirds in relation to the estimated timing of the (non ice-associated) summer bloom (match-mismatch hypothesis).
- Additional hypotheses that emerge from field studies and other retrospective modeling efforts may be tested using the same statistical modeling framework. For example, if additional long-term indicators of productivity for other important components of the ecosystem become available from ongoing ecosystem modeling efforts (Kerim Aydin, pers. comm.) or seabird and marine mammal studies, they will be incorporated in the analyses as appropriate.

Project Reporting

Research Products: The observed responses of selected upper trophic level species will be summarized and made available in one or more of the following forms: (1) Means and variability of the response variables (survival, recruitment, condition) during warm and cool periods, (2) The functional form of observed relationships that provide the "best" fit to the observed data (as determined by model selection criteria such as the Akaike Information Criterion), and (3) Specific parameters that describe the observed relationships (estimated regression coefficients) between climate variables and productivity and their uncertainty (variance).

Research Links: This project will require time series of seabird productivity (fleging success and breeding phenology) form the colony-based seabird component (O4.37), time series of historical fur seal counts and productivity from the patch dynamics study (O4.62), and trawl survey data from the bottom-trawl survey (O2.25). Physcial data from the biophysical moorings (O1.1) will be required to update stratification indices, and indices of forage fish abundance near the Pribilof Islands (age-1 pollock) may be incorporated in the analysis as they become available. Time series of environmental variability and biological indices compiled during this study will be made available to all investigators and research products will be disseminated primarily to the modeling group.

Research Reporting: The covariation analysis will be completed and results will be shared with the modeling group by the end of the third quarter of 2008. The analysis of Pacific cod, flatfish, and crab productivity and testing of relevant *a priori* hypotheses will be completed by the end of 2009. Analyses of seabird, and marine mammal productivity will be completed by the spring of 2011. Results from these analyses will be delivered to the modeling group at the end of 2009 and in the spring of 2011. Manuscript will be submitted to peer-reviewed journals during 2009 (covariation), 2010 (cod, flatfish, and crab variability), and 2011 (seabird and mammal variability, trophic interactions).

Dissemination: Peer reviewed, scientific publications will follow the completion of each research component. We anticipate a minimum of 5 scientific publications that will cover at least the following topics:

- Covariation and trophic interactions among fish, seabirds, and fur seals in the southeastern Bering Sea
- Climate effects on productivity of major groundfish species (cod, flatfish, crab) in the southeastern Bering Sea
- Climate effects on the availability of prey for seabirds and fur seals in the Pribilof Islands
- Climate effects on multi-species interactions in the southeastern Bering Sea (synthesis paper)

Some of these topics, in particular the productivity of major groundfish species, may result in more than one paper. The synthesis paper may also incorporate results from a related biomass dynamics modeling effort, if funded (M.61).

Graduate Students and Post-docs: None

Figures and Tables

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. BSIERP 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.

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