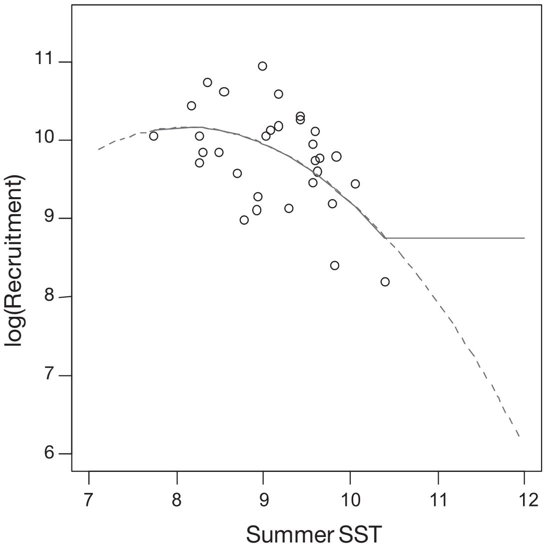
Integrating Ecosystem Aspects and Climate Change Forecasting into Stock Assessments

by Anne B. Hollowed, Teresa A'mar, Steven Barbeaux, Nicholas Bond, James N. Ianelli, Paul Spencer, and Thomas Wilderbuer

There is growing recognition that global climate conditions are changing. Understanding what these changes are and how they impact the Earth's marine ecosystems are two of NOAA's strategic goals. In response, scientists at the Alaska Fisheries Science Center's (AFSC) Status of Stocks and Multispecies Assessment (SSMA) program have collaborated with climate scientists and oceanographers at the Pacific Marine Environmental Laboratory (PMEL) to develop new modeling tools to better project how climate change will alter the production and distribution of commercial fishes off Alaska. The models provide science-based support for long-range spatial planning and management of these commercial fisheries. This partnership between NOAA branch offices serves as an example of how NOAA can build interdisciplinary research teams to inform managers and the public of the timing and magnitude of the impacts of climate change on commercial fishes.

The following article is designed to provide the reader with an overview of some of the outcomes of this collaborative modeling activity and to introduce the reader to the types of modeling approaches currently employed by scientists within the SSMA program. Three examples of methods for incorporating climate change scenarios into stock assessments and two examples of statistical methods for evaluating climate impacts on fish distribution are presented. Each example was informed by advancements in understanding the mechanistic linkages between climate, the ocean, and marine fish and fisheries, which allowed analysts to develop functional relationships for use in stock projections. The studies relied on the AFSC's innovative approach to data collection, which includes real-time oceanographic data acquisition aboard active fishing and research vessels. Valuable knowledge of the functional relationships linking fish responses to climate or ocean forcing was obtained from process-oriented research conducted by the AFSC Ecosystems Fisheries and Oceanography Coordinated Investigations program (Eco-FOCI). The advancements in modeling capability were facilitated by funding from the National Marine Fisheries Service (NMFS) Fisheries and the Environment (FATE) program, the Bering Sea Integrated Research Program (BSIERP) funded by the North Pacific Research Board (NPRB), and the Bering Sea Ecosystem Study (BEST) funded by the National Science Foundation.

Figure 1. Summer temperature effect used to model the relationship between climate-change models and pollock recruitment (from Mueter et al. 2010).



Evaluating Management Strategies for Eastern Bering Sea Walleye Pollock in a Changing Environment

James Ianelli, Anne Hollowed, Alan Haynie, Franz Mueter (University of Alaska) and Nicholas Bond (PMEL) performed an evaluation of management strategies for eastern Bering Sea (EBS) walleye pollock (*Theragra chalcogramma*). The analysts recognized that applying the best available information for fisheries management advice is becoming more complex as the number of stocks or stock components considered increases. Stock assessments contain uncertainty; adding more realistic functional relationships (e.g., predator/prey or environmental effects on life history) generally inflates the uncertainty on stock dynamics. BEST/BSIERP investigators conducted retrospective studies to improve our understanding of how climate change may impact production of EBS walleye pollock. These studies revealed a dome-shaped relationship between summer sea surface temperature and pollock recruitment success (Fig. 1). Future population simulations with this relationship were used to identify harvest strategies that are robust to shifting production regimes. The status quo harvest policy was contrasted with six alternative strategies under two types of recruitment pattern simulations: one that follows temperature-induced trends (Fig. 1) and the other that follows a stationary recruitment pattern similar to historical observations. A subset of 82 climate model scenarios provided by the Intergovernmental Panel on Climate Change (IPCC) provided temperature inputs (Fig. 2) from which an additional 100 stochastic simulated recruitments were generated to obtain the same overall recruitment variability as observed for the stationary recruitment simulations.

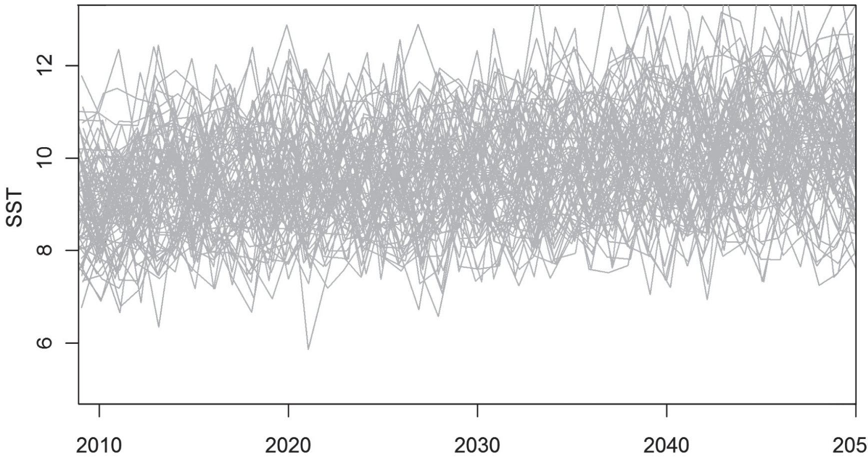


Figure 2. Time series of future eastern Bering Sea sea surface temperatures based on the selected 82 climate-change models.

This study presented a simple evaluation of how harvest control rules under a regime with lower mean recruitment will likely result in increased likelihood that the stock will decline and that fishery production will decrease. This type of evaluation provides a quick way to evaluate critical environmental conditions against alternative tactical harvest policies. For communication purposes, indicators were developed and designed to be transparent to stakeholders. Additionally, an integrated approach for combining indicators was developed so that the relative importance of different factors can be elicited by stakeholder involvement.

Under the no climate change projections, the status quo harvest control rules perform well. Under the climate change, temperature-induced projections, the status quo management with static reference points (e.g., the overall 2 million metric tons (t) limit for all groundfish catch and efforts to manage perceived forage requirements for Steller sea lions) will result in much lower average catches and an increased likelihood of fishery closures (Fig. 3). Evaluation of alternative management strategies shows that a policy that reflects gradual changes in carrying capacity tended to outperform others under the climate change, temperature-induced scenarios.

Related studies suggest that summer temperatures may be a proxy for other processes influencing pollock survival. BEST/BSIERP investigators have found a relationship between temperature and the energy content (and hence viability) of young-of-year pollock. Colleagues at the AFSC Auke Bay Laboratories (ABL) have developed this further with the rationale that an index of temperature change between the average June sea surface temperature in year t (during the age-1 stage) and the average August sea surface temperature in year t-1 (during the age-0 stage) is positively correlated with subsequent recruitment. Lower differences are hypothesized to represent a cool late summer during the age-0 stage followed by a warm spring during the age-1 stage, which leads to favorable pollock survival based on the energy density hypothesis. Using this relationship, with the cool late summer last year and warmer spring this year, ABL scientists predict about 48 billion age-1 pollock in 2011. If the relationship holds, this indicates that the 2010 year class would be similar in magnitude to the 1996 year class.

Investigators recognize that other factors may influence pollock survival during the first year of life. Past assessments for EBS pollock have evaluated the impact of larval drift characteristics after peak spawning (as an impact on subsequent recruitment) and the impact of temperature on survey availability/catchability. More recently, scientists from the AFSC Midwater Assessment and Conservation Engineering (MACE) program have made progress comparing euphausiid abundance with pollock distribution using acoustic survey methods. In particular, the index of euphausiids has indicated a marked increase since 2004, and the spatial patterns of pollock appear to be coincident with euphausiid density.

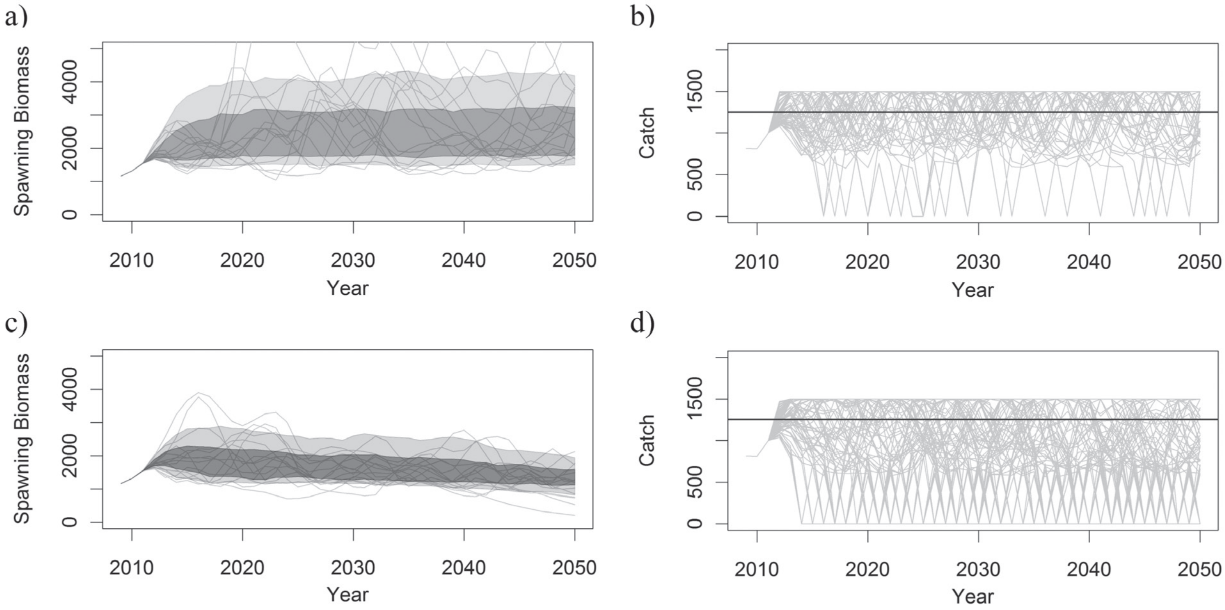


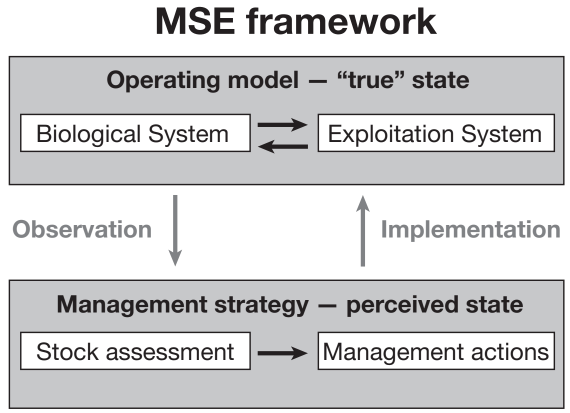
Figure 3. Projected eastern Bering Sea pollock spawning biomass and catch under the **current harvest control** rule with stationary environmental conditions (panels a and b) and under the 82 IPCC models selected for eastern Bering Sea sea surface temperatures (panels c and d). For the spawning biomass figures, the shaded swaths represent 25th and 75th percentiles (dark shade) and 10th and 90th percentiles (light shade). Individual lines represent results from a single Monte Carlo trial. Dark lines in panels b and d represent the approximate historical average catch of pollock in the eastern Bering Sea.

The approaches presented here make simplifying assumptions including the assumption that pollock production is primarily driven by bottom-up forces that can be appropriately indexed by summer temperature. There are numerous examples where control mechanisms that were identified in one regime no longer apply in a new environmental state of nature. To this end, a large-scale model is being developed at the AFSC whereby the physical oceanography is modeled jointly with plankton and fish production. This more "realistic" model will help highlight the additional factors that affect the complex ecosystem dynamics.

Management Strategy Evaluation for the Gulf of Alaska Walleye Pollock and Pacific Cod Fisheries

An extension of the method described above is a formal management strategy evaluation (MSE) that incorporates feedbacks from decision rules within the simulation testing framework (Fig. 4). The MSE approach has been used in natural resource management to examine how robust management strategies are to error and uncertainty. An MSE involves using an operating model to represent the "true" underlying population dynamics of the stock and the harvest system, and a management strategy (usually a stock assessment model and a harvest control rule) to determine management actions. The structure of the management strategy can be designed to achieve management objectives; a discussion of management priorities and desired outcomes is necessary before quantifying the objectives into performance metrics. These metrics quantify how effective the management strategy is in achieving the management objectives.

Teresa A'mar, André Punt (University of Washington), and Martin Dorn performed a MSE on the management strategy used by the North Pacific Fishery Management Council to manage the Gulf of Alaska (GOA) walleye pollock fishery. The current harvest control rule and several alternative management strategies were evaluated with respect to error, uncertainty, alternative hypotheses for the stock-recruitment relationship, and environmental forcing. The "true" population dynamics, represented in the base operating model, were consistent with the 2005 stock assessment. The operating models were fit to the stock assessment data using Bayesian statistical methods and then simulated populations were subjected to the harvest constraints of different management strategies given the perceived stock status estimated with parameter uncertainty and process and observation error. The management objectives included keeping spawning biomass near the reference level of 40% of the estimated unfished spawning biomass level and achieving high stable catches without exceeding the overfishing limit.



From Fromentin and Kell, 2007

Figure 4. The management strategy evaluation framework

Extensions to the base operating model were made to incorporate proxies for environmental forcing: 1) historical annual natural mortality-at-age for pollock was linked to the historical biomass of pollock predators arrowtooth flounder (*Atheresthes stomias*), Pacific cod (*Gadus macrocephalus*), and Pacific halibut (*Hippoglossus stenolepis*) through predator-prey functional responses, and future annual natural mortality-at-age was then predicted from the projected biomass of the pollock predators; 2) changes in future average recruitment were based on historical patterns in average recruitment which characterized environmental regime shifts; and 3) historical annual recruitment was linked to historical climate indices, and future recruitment was then projected using the future climate indices generated from downscaled general circulation model (GCM) output from the IPCC AR4 models which characterized environmental variability and climate change.

Ongoing research by Teresa A'mar and Grant Thompson includes developing an MSE for the GOA Pacific cod fishery that is similar in structure to that for the GOA walleye pollock MSE. The GOA Pacific cod MSE incorporates more fishing gear types and fishing seasons and fewer surveys than in the GOA walleye pollock MSE. The significant change in data and data types has led to difficulty in getting the operating model for the GOA Pacific cod MSE to match the results of recent stock assessments for GOA Pacific cod.

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Incorporation of Climate Indices into Flatfish Stock Assessments

Thomas Wilderbuer, Nicholas Bond, Anne Hollowed, James Ianelli, Elizabeth Matta, Dan Nichol, and William Stockhausen developed models to incorporate climate information in the EBS flatfish stock assessments. Three types of environmental effects on flatfish behavior and biology were considered with respect to estimated:

1) survey catchability,
2) recruitment, and
3) somatic growth.

Survey catchability: For flatfish in general, the nonlinear modeling of catchability attempts to quantify the susceptibility of a species to capture in survey bottom trawls. Factors affecting catchability include fish being herded from the area where the trawl bridles contact the seafloor into the path of the trawl and losses due to escapement under the footrope of the trawl. This behavioral response appears to be related to temperature effects on flatfish metabolism. Studies using annual bottom temperatures indicate a positive relationship—warmer conditions indicate greater catchability to the survey gear. These relationships have been applied in the EBS yellowfin sole, flathead sole, and arrowtooth flounder assessments.

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For yellowfin sole, temperature-effects on catchability may also reflect their availability to the survey area. Yellowfin sole are known to undergo annual migrations from wintering areas off the shelf-slope break to nearshore waters where they spawn throughout the late spring and early summer months at the same time that the survey is conducted. Exploratory survey sampling in coastal waters of the eastern Bering Sea indicates that yellowfin sole concentrations can be greater in these shallower areas not covered by the standard AFSC survey. Commercial bottom trawlers have commonly found high concentrations of yellowfin sole in areas such as Togiak Bay and in more recent years in Kuskokwim Bay to just south of Nunivak Island (Fig. 5). These coastline areas are sufficiently large enough to offer a substantial refuge for yellowfin sole from the current survey.

Over the past 25 years, survey biomass estimates for yellowfin sole have shown a positive correlation with shelf bottom temperatures. The spatial effects may also relate to the timing of migration. In warmer years, yellowfin sole spawn earlier and, hence, more fish may be available to the survey gear and station locations.

Recruitment: Environmental conditions also impact survival of early life stages and subsequent recruitment to the fisheries. Climate indices were recently evaluated for Bering Sea/Aleutian Islands northern rock sole and appeared to be related to recruitment. Northern rock sole recruitment appears to vary on a decadal (or shorter) scale due to climate influences on survival during the early life history period. After spawning in February-March, northern rock sole larvae are subject to advection from wind, currents, and tidal forcing during April-June. Using an ocean surface current model, wind-driven advection of larvae towards favorable nursery areas in the inner domain coincided with above-average recruitment. The inner domain of the Bering Sea is a productive region due to tidal mixing. Ocean forcing resulting from on-shelf (easterly) winds during the 1980s and again in 2001-03 coincided with periods of above-average recruitment, whereas off-shelf (westerly) winds during the 1990s corresponded with periods of poor or average recruitment (Fig. 6). This suggested that future recruitment for northern rock sole will depend on wind patterns as driven by future climate conditions. Thus, to predict future recruitment for northern rock sole, it is also important to have a reliable prediction of future climate conditions (springtime winds).

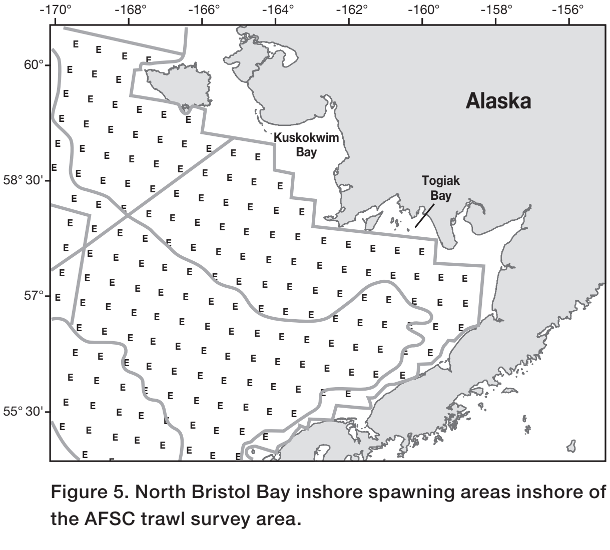

Figure 5. North Bristol Bay inshore spawning areas inshore of the AFSC trawl survey area.

Future climate conditions were developed based on spring wind conditions (affecting advection) from a weighted ensemble of IPCC model output. The various IPCC models used were rated based on how well their hindcasts for the latter half of the 20th century matched observations. The two specific criteria for this rating were the IPCC model's ability to reproduce the overall mean April-June winds on the southeast Bering Sea shelf and the interannual variance in the seasonal mean winds. The weightings for each model were then used to form a projection of the winds out to the year 2050 and converted to ending longitude of surface-drifting larvae. This projection, with the attendant year-to-year variability, indicated a slight tendency towards increased shoreward transports, with substantial variability on top of this weak trend.

Based on these results from the IPCC climate models, the future production of northern rock sole was projected for the period 2001-50. A hierarchical bootstrap algorithm was applied to estimate the annual variability in future springtime climate (i.e., wind direction and subsequent larval drift) as well as variability in recruitment under a given climate condition. These results suggest a moderate increase in expected recruitment over time because the trend indicates more frequent occurrence of the on-shelf climate condition through 2050, which corresponds to the highest expected mean recruitment. However, this analysis assumed all recruitment variation was due to this climate driver. In reality, other factors will affect recruitment. If other factors are uncorrelated with the IPCC factors, then the expected trend may be realized, albeit with a greater range of uncertainty.

Somatic growth: Otolith increment analyses conducted by members of the AFSC Age and Growth program have found further climate associations with yellowfin sole somatic growth. A statistically significant correlation was found between otolith increment growth and May sea surfuce temperature (SST) (Fig. 7). The next step is to include this source of variability within the stock assessment where alternative growth models are entertained (Fig. 8). Previous assessments have used time-invariant growth.

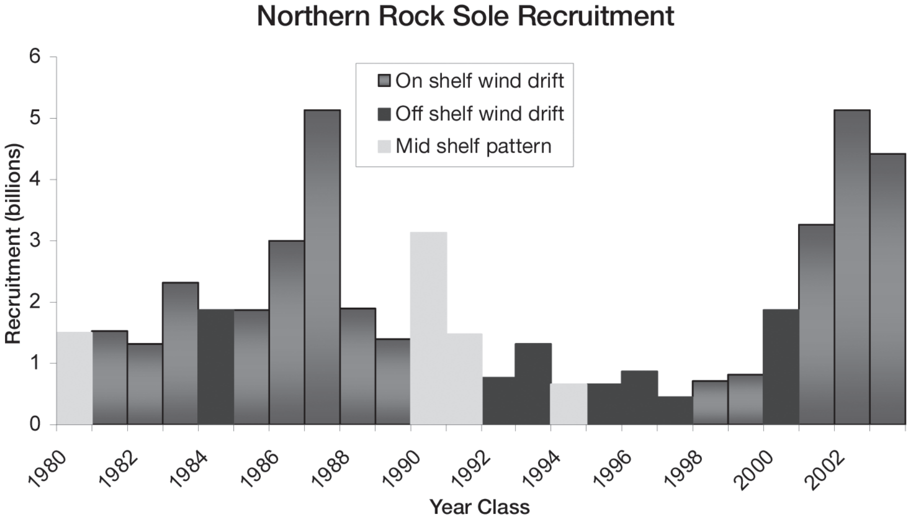

Figure 6. Estimated northern rock sole age-1 recruitment (billions) for 1980-2003 from the stock assessment model. Shades represent different wind patterns affecting drift.

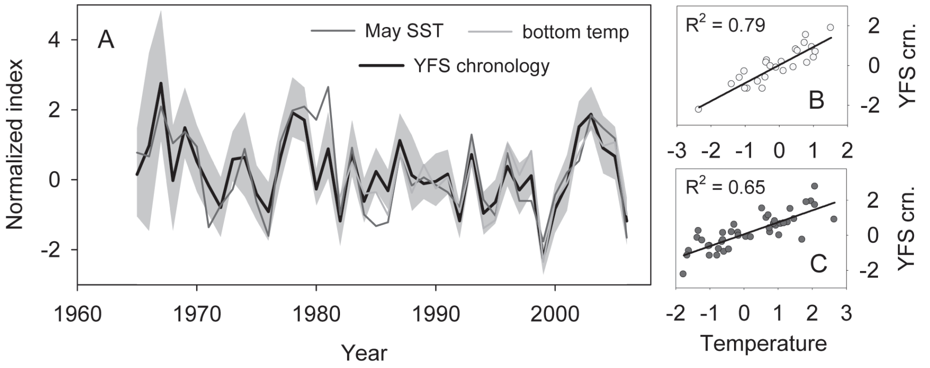

Figure 7. A) Yellowfin sole otolith growth-increment chronology developed using regional curve standardization. Gray area represents 95% confidence intervals for each calendar year. Also shown are summer bottom temperatures and May sea surface temperatures for the eastern Bering Sea. All time series were normalized to a mean of 0 and standard deviation of 1. B) Bivariate plot of the yellowfin sole chronology and bottom temperatures. C) Bivariate plot of the yellowfin sole chronology and May sea surface temperatures.

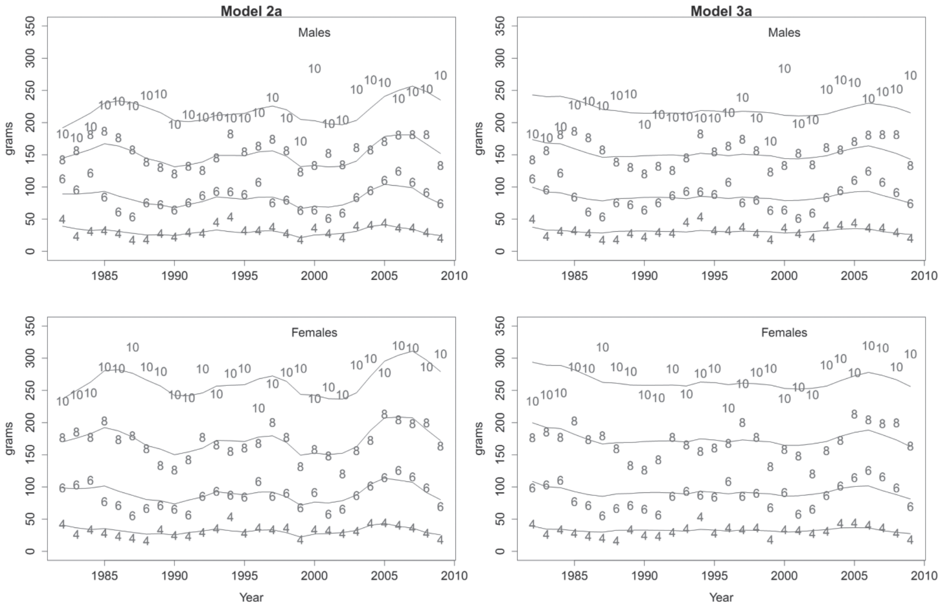

Figure 8. Mean body mass (g) for selected ages of yellowfin sole under alternative models of growth (right and left sides) by sex (upper and lower panels). The lines represent model estimates whereas the individual numbers (ages) represent the mean values from trawl survey data, 1982-2009.

Climate Impacts on Arrowtooth Flounder Distribution in the Eastern Bering Sea

Paul Spencer, Nicholas Bond, and Anne Hollowed are examining how environmental conditions on the EBS shelf may affect the spatial distribution of arrowtooth flounder. Based on data from 1982 to 2006, Spencer found that arrowtooth flounder avoid the cold pool (bottom water ≤2°C generally located in the central shelf of the EBS). An increase in the area of the cold pool in recent cold years (2007-10) has been accompanied by a reduction in the area occupied by arrowtooth flounder and a lower proportion of the population in the central shelf (Fig. 9). A relationship between cold pool area and arrowtooth flounder spatial distributions can be used to project spatial distributions under future environmental conditions, which are useful in assessing the potential predation impacts upon walleye pollock. These projections require: 1) using climate models to predict the future area of the cold pool, and 2) using empirical relationships between cold pool area and the area and location of arrowtooth flounder distributions to predict future spatial distributions.

Because many climate models do not predict the cold pool directly, cold pool predictions were based on identifying empirical relationships between cold pool area and environmental variables and predicting future cold pool area based on predictions of these environmental variables. Sea level pressure and maximum sea ice extent were found to be strong predictors of the cold pool, and cold pool projections from 2010 to 2050 were obtained from projections of these variables from 15 global climate model simulations developed by the IPCC. Projections of cold pool area show a wide range of variability but an overall decreasing trend. The predicted area and latitude of arrowtooth flounder spatial distributions, based on empirical relationships with cold pool area, increased from 2010 to 2050.

Changes in the spatial distribution of arrowtooth flounder can influence their overlap with the spatial distributions of prey, of which age-1 and age-2 pollock comprise a large portion. Age-1 pollock have been observed to have high densities within the cold pool. If the future availability of age-1 pollock in the southern middle shelf is reduced due to a reduction in the cold pool, other areas (such as the northwest shelf) may show larger abundance gains for arrowtooth flounder with future shifts in spatial distributions.

Projections of future predatory impacts of arrowtooth flounder will require projections of overall abundance and how the population is distributed among various EBS sub-areas. Future work will examine the relationships between the area occupied by arrowtooth flounder within various EBS sub-areas and cold pool extent in order to develop a simple model to project future spatial distributions.

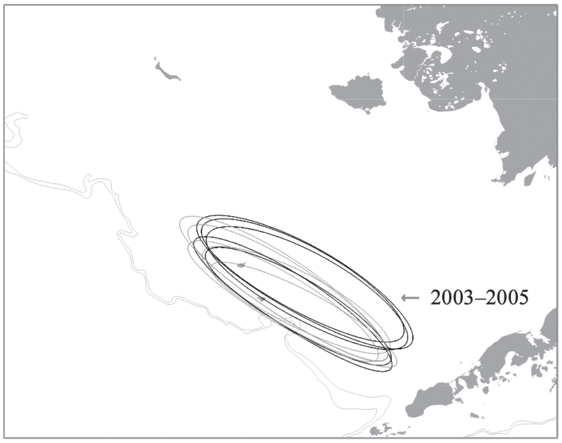

Figure 9. Ellipses representing 30% probability contours of bivariate normal distributions fit to EBS survey CPUE data for arrowtooth flounder for the five coldest (gray; 1994, 1999, 2008-2010) and warmest (black; 1996, 1998, 2003-2005) years from 1982 to 2010.

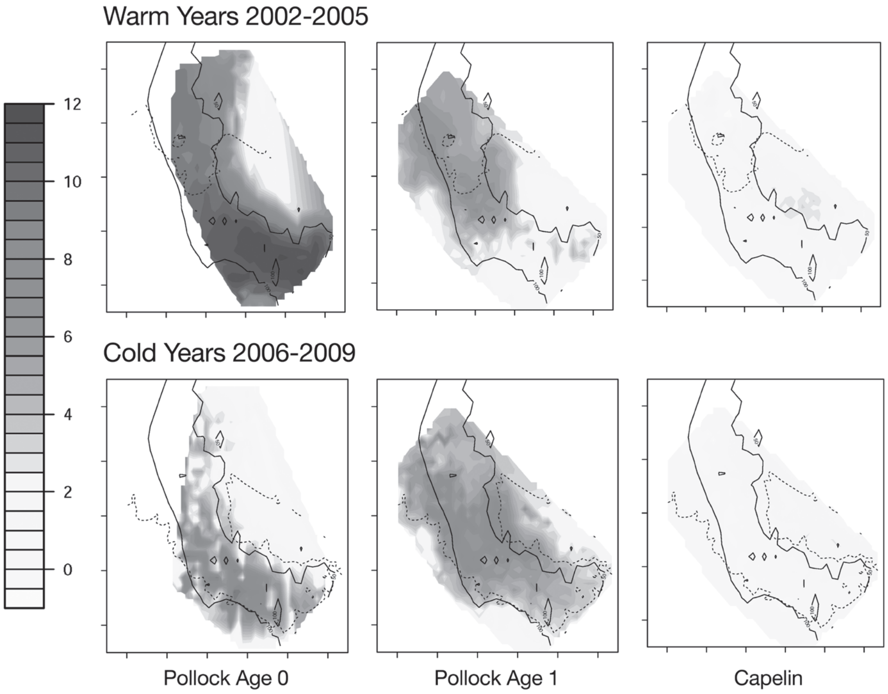

Figure 10. GAM predicted spatial surfaces of ages 0 and 1 pollock with capelin density contoured as log(number per km_2) in warm and cold years.

Climate Impacts on Forage Fish Distribution in the Eastern Bering Sea

Anne Hollowed, Steven Barbeaux, Ed Farley, Edward D. Cokelet (PMEL), Stan Kotwicki, Patrick Ressler, Cliff Spital, and Christopher Wilson examined whether climate variations influenced the boundaries of suitable ocean habitat, and whether these changes affected the spatial distribution and interactions between three groups of forage fish in the Bering Sea: age-0 and age-1 walleye pollock and capelin, *Mallotus villosus*. Statistical analysis was performed on NMFS acoustic trawl, surface trawl, and bottom trawl survey data collected in the Bering Sea between 2004 and 2009. Habitat boundaries were defined using key explanatory variables including depth, bottom temperature, and surface temperature, using general additive models. Bathymetry, bottom temperature, and frontal zones formed boundaries between different groups of forage fishes. General additive models (GAMs) were developed to project spatial distributions of forage fish in warm and cold conditions (Fig. 10). The results showed age-0 pollock were dispersed throughout the middle domain in well-stratified regions. In cold years the highest densities of age-0 pollock were found in the southern regions of the middle domain waters in warmer than approximately 1°C. Age-1 pollock were observed on bottom over the middle domain (50-100 m depth) and along the 100-m isobath in midwater. In both warm and cold years, capelin were concentrated in the inner domain, a well-mixed region. These findings suggest that forage fish have adopted life history strategies and habitat associations that partition space across the Bering Sea. These statistical models and the mechanisms they reveal provide the basis for predicting the spatial distribution of forage fish under future climate change.

Summary and Conclusions

Retrospective analyses and current field studies suggest that the distribution and abundance of groundfish stocks off the coast of Alaska will probably be influenced by climate change. AFSC and PMEL scientists incorporated proposed linkages between climate forcing and fish distribution, growth, or abundance to project the implications of climate change on commercial fishes and commercial fisheries. These simulation models have been used to inform fisheries management decisions in the Gulf of Alaska and Bering Sea. As with any model, there are inherent deficiencies for each of these models. These models are intended to contribute to the ensemble of modeling tools that will be used to assess, predict, and understand the effects of climate change on commercial fish species in waters off the coast of Alaska.