Evaluating ecosystem indicators performance under climate change

Principal Investigators: Kerim Aydin, Stephani Zador, NOAA Alaska Fisheries Science Center; André E. Punt, School of Aquatic Fisheries Science, University of Washington

Collaborator: Ivonne Ortiz, School of Aquatic Fisheries Science, University of Washington

Background: Within the Alaska region, the Ecosystem Considerations Chapter of the Alaska Fisheries Science Center's (AFSC) Stock Assessment and Fisheries Evaluation Report has evolved to provide indicator-based ecosystem assessments and report cards for the eastern Bering Sea (EBS) and Aleutian Islands (Zador 2012). Development of these assessments involved interdisciplinary teams that selected physical, biological and socioeconomic ecosystem indicators that can be tracked and evaluated on a yearly basis. Ten broad, community-level indicators were chosen for the EBS based on their potential to determine the current state and likely future trends of overall ecosystem productivity. Annual updates to the ecosystem assessment synthesize information based on indicator status to inform the North Pacific Fishery Management Council. The ecosystem assessment is presented to the Council in direct conjunction with the quota-setting process, and so has allowed the Council to make direct quantitative adjustments to Allowable Biological Catches in response to specific ecosystem-wide indicators. The next direct steps, identified by the Council, are to develop and test formal thresholds for these indicators to trigger specific management actions.

Recent approaches to integrated ecosystem assessment (IEA) propose that risk analysis be included specifically in the process to determine the probability that an ecosystem indicator will reach or remain in an undesirable state (Levin et al. 2009). Studies such as Fulton et al. (2004) and Link et al. (2009) have tested ecological indicators under different fishing scenarios. However, their analyses have generally assumed constant climate conditions. For the Alaska region, most ecosystem indicators are based on fisheries survey data, and their response behavior has only been tested under past environmental/climate conditions. Because adequate prediction of future climate is challenging, our interest lies in understanding and testing how key ecosystem indicators may vary, as well as the implications of this variability, so as to inform the development of management strategies that are resilient to climate variability and climate change. As first proposed by Hollowed et al. (2011), we will use outputs from the recently completed simulations of the high resolution ocean and lower trophic models (NEP5-NPZD) developed as part of the Bering Sea Project (bsierp.nprb.org) (Wiese et al. 2012) to explore these ideas. We assume the NEP5-NPZD models are our current best representation of the eastern Bering Sea shelf ecosystem and propose to investigate whether the output from the hindcast replicates the time series of selected ecosystem indicators, and to use the output from the forecasts to test the behavior of these indicators under three different climate forecasts as predicted by three different IPCC climate model projections.

The Bering Sea Project (Wiese et al. 2012) was designed to pair field work and historical data analysis with modeling of the different ecosystem components, all linked through a vertically integrated model that is then used as the operating model for Management Strategy Evaluation. The vertical model has been described in Aydin et al. (2010), was developed and validated independently, and includes climate, oceanography (ROMS/NEP5)and lower trophic levels

(NPZD) as some of its components. The model is spatially-explicit, with a resolution of ~10 km, and the subgrid used (Bering Sea grid) has a geographical extent from the western Gulf of Alaska to the Russian coast and slightly past the Bering Strait. The climate, oceanography and lower trophic components are finished, and their hindcasts and forecasts are readily available.

The hindcast for the NEP5-NPZD covers the years 1970 to 2009. The Common Ocean Reference Experiment reanalysis (CORE; Large and Yeager, 2008) was utilized for the years 1969-2004 while the Climate Forecast System Reanalysis (CFSR; Saha et al., 2010) was utilized for the years 2003-2009. These two reanalyses were combined to have a continuous hindcast from 1979 to 2009 since CORE spans from 1950-2004 and CFSR spans 1979-present. Overlapping runs for 2003 and 2004 allowed a comparison of results using the two reanalyses; these were used to adjust CFSR for compatibility with CORE (Hermann et al. in prep). The forecasts (2005-2035) were run under three IPCC climate models: CGCM-t47 (low ice), ECHO-G (high ice) and MIROCM (medium ice). These climate models were found to perform well for the Bering Sea (Wang et al. 2012) based on their ability to capture decadal variability (e.g. the Pacific Decadal Oscillation) and ice dynamics (Wang et al. 2009).

ROMS/NEP5 is a coupled ocean-sea ice model described and evaluated by Danielson et al. (2011), which builds on a model described by Curchitser et al. (2005). Danielson et al. showed ROMS/NEP5 closely reproduces ice cover and spring ice retreat onset. Its main strengths include its ability to reproduce 85% of the interannual variability in the integrated sea ice extent, and to account for almost 50% of the variance in monthly temperature anomalies, as measured at 10m and 60m at mooring M2 (57°N, 165°W) and then regional statistics at 10m and 70m. NPZD is the lower trophic model coupled to NEP5 specifically designed to incorporate the ice dynamics of the Bering Sea and models nutrients, phytoplankton, copepods, euphausiids and detritus. The model has been described and tested by Gibson and Spitz (2012) as well as reviewed by a team of field biologists part of a synthesis project funded by the National Science Foundation (Mordy and Lomas 2012).

Based on the documented performance of the climate models, NEP5-NPZD, and a review of the ecosystem indicator time series updated annually for the EBS (Zador 2011), we propose to use the following three ecosystem indicators to evaluate the ecosystem physical structure and lower trophic levels of the EBS: i) sea ice retreat index, ii) extent of cold pool, and iii) mean zooplankton biomass.

We chose the seasonal ice retreat index for testing and simulation because it has not performed well as an indicator in past, very warm years. It is defined as the number of days past March 15 when sea ice coverage is greater than 10% in a 2^o x 1^o box (bounded by 56.5^o to 57.5^o N, 165^o to 163^o W) on the southern EBS shelf. However, in 2000-2005 sea ice coverage was less than 10% by March 15, so the index did not provide any information about the difference in ice retreat among those warm years. Mueter and Litzow (2008) found sea ice extent to influence the biogeography of the groundfish community and explain 57% of the variability in commercial snow crab (*Chionoecetes opilio*) catch, thus this index tracks variability important to current commercial fisheries.

The second index, cold pool extent, is defined by bottom temperatures less than 2°C. It is related to ice extent in that sea ice creates a pool of cold bottom water on the eastern Bering Sea continental shelf, and this cold pool has been shown to influence the latitudinal and longitudinal distribution of the groundfish community, including several important commercial species (Kotwicki et al. 2005; Spencer, 2008; Meuter and Litzow 2008 Stevenson and Lauth 2012). This in turn changes the spatial distribution of fishing effort (Haynie and Pfeiffer 2012). The cold pool also influences water mixing and water stratification (Stabeno et al. 2012). Studies have implicated warmer temperatures as the primary reason for changes in the distribution of forage fish and benthic infauna community in the eastern Bering Sea shelf (Coyle 2007; Hollowed et al. 2012). Warming could have further impacts on the EBS from changing the timing of the spring phytoplankton bloom, to favoring the northward advance of subarctic species and retreat of arctic species (Stabeno et al. 2007, 2010, 2012).

The third index, mean zooplankton biomass, is the mean of four regional zooplankton biomass survey estimates: basin, outer shelf, middle shelf and coastal. The predictions of copepods and euphausiids from the NPZD can be used as-is to test different ways of combining measurements of copepods and euphausiids, and suggest potential new indices to substitute the current use of combined zooplankton biomass because this model tracks copepods and euphausiids.

Objectives: **1.** To evaluate the current ability to reproduce actual ecosystem indicator time series using output from the hindcast of the NEP5-NPZD model. These indicators include sea ice retreat, extent of the cold pool, and mean zooplankton biomass.

2. To evaluate whether these ecosystem indicators remain sensitive and informative under climate change using forecast output driven by three different climate models.

Approach Objective 1: For the physical indicators (sea ice retreat and cold pool extent), the main interest is to quantify the accuracy of the model values, so as to define a baseline variability that will help evaluate the forecasts. For the zooplankton biomass index, the main focus is its use as a proxy for secondary production. We will first use the readily available output from the hindcast (1970-2009) to reproduce the time series for the three ecosystem indicators described above. The outputs for the hindcast and forecasts will be extracted from stored results of the NEP5-NPZD model (our operating model). Our intent is to first reproduce –to the extent possible- the data collection and calculation process for each index (sampling model), and then perform a correlation analysis (Pearson and/or Spearman) and pattern similarity (Taylor diagrams) of modelled (both from the operating and the sampling model) vs. data-driven time series (see table below). This will provide a quantitative assessment of the ability of the ROMS/NPZD to reproduce observed patterns in the ecosystem indicators time series and the ability of the indicator to capture the dynamics of interest. The table below summarizes the attribute and indicators tested.

Approach Objective 2: We will generate time series of the operating model values based on the available forecast outputs (2012-2035) using the algorithm (sampling model) developed to generate the time series from the hindcast and evaluate the performance of the indicators under different climate scenarios using regression analysis and pattern similarity analysis (or some other statistical method) We will also estimate the trend for each of the indicators and compare both trends and correlations across climate scenarios. For the sea ice retreat index, we know there have been already years when the index does not perform well –those years when the ice coverage was less than 10% before March 15, the reference date. We will propose new reference dates or fixed spatial references so that ice retreat remains an informative indicator even under warmer climate conditions. Given the decreasing trend in ice extent estimated from various IPCC model forecasts (Wang et al. 2012) for the eastern Bering Sea, we expect to get three different forecasts as to the decrease of the cold pool extent and its spatial shift, as well as evaluating the standard sampling grid as an adequate sampling grid even under warmer climates. Though most of the analysis is numerical, we will also generate maps of the spatial extent of the cold pool. For the third index, we will test combinations of euphausiid-copepod indices to replace the current zooplankton biomass index.

Index/ Attribute	*Proxy / operating model value*	*Estimator/sampling model to replicate using NEP5*
Sea ice retreat/ Surface physical habitat	number of days after onset of ice retreat when sea ice coverage is greater than 10% on the southern EBS shelf calculated from ice cover estimates on the NEP5 10km grid over the simulated period	number of days past March 15 when sea ice coverage is greater than 10% in a 2^o x 1^o box (bounded by 56.5 ^{o} to 57.5 ^{o} N, 165 ^{o} to 163 ^{o} W) on the southern EBS shelf, calculated from ice concentration estimates derived from satellite imagery using the Bootstrap algorithm for data 1978-present
Cold pool extent/ Bottom physical habitat	area with temperatures less than 2^oC, extended down the middle shelf to the Alaska Peninsula and into Bristol Bay as measured on the bottom layer of the NEP5 10km grid at a given point in time	area with temperatures less than 2^oC, as measured on stations of the RACE bottom trawl survey sampled during summer
Zooplankton mean biomass/ Secondary production	wet weight (mg/m^3) of copepod and euphausiid biomass in the EBS basin, outer shelf, middle shelf and coastal water over the water column of the basin, outer shelf, middle shelf and coastal water during summer	Average of the wet weight (mg/m^3) of zooplankton biomass in the EBS basin, outer shelf, middle shelf and coastal water as measured on stations by the T/S Oshoro Maru during summer

Finally, we will compare these forecasts to provide a range of variability stemming from different climate models which will provide a context to the state of the ecosystem in view of the projected scenarios. This range is not meant to be exhaustive and is meant only as an example of potential degrees of variation that can be included as a mean forecast baseline for risk analysis where the state of the ecosystem is compared to expected conditions under warmer climates. We plan to choose conditions below and above the historical mean for each ecosystem indicator (e.g. one standard deviation above and below historical mean) and provide the frequency and magnitude of such events in the forecasted time series so as to inform how often these events can be expected in the future. While three forecast time series may not be enough to properly estimate the likelihood of these events, this exercise will provide a basis to add on as more forecasts become available. Both the ensemble mean of the forecasts and the expected frequency of events can provide a baseline to anchor risk analysis given climate change

Benefits: First, we will evaluate the use of the NEP5-NPZD model outputs to reproduce time series of ecosystem indicators. While the model has been tested for sea ice coverage and temperature, its use as a platform to replicate these ecosystem indicators has not been tested. Both sea ice retreat and bottom temperature play major roles in the distribution and community composition of the eastern Bering shelf. As byproduct, the forecast time series will provide a quantitative estimate of the indicators' trends under different future climate scenarios. This trend and variability will inform the development of better indicators so that they remain informative despite warmer climate conditions. The availability of the forecasted indicator time series will also facilitate further incorporation of potential climate change effects into other biological processes or fish population models. If successful, this project would serve as validation for the use of this model as a platform to develop and test other ecosystem indicators.

This project will directly address indicator development and risk analysis, two of the steps proposed for an IEA by Levin et al. (2009). It is of primary importance to test the response and information content of ecosystem indicators under future climate scenarios because the eastern Bering Sea is particularly vulnerable to warmer climate conditions. We may be able to improve those indices or qualities of the indices that currently fail to respond under warmer conditions by testing current indicators under forecasted conditions; any improvements will be incorporated into future ecosystem assessments. The cold-warm variability of ice retreat and bottom temperature in the last 10 years in the eastern Bering Sea has proven to have short-term consequences for management and economic impacts (Meuter and Litzow 2008; Haynie and Pfeiffer 2012). Evaluating the different forecasts in terms of the frequency and magnitude of similar conditions, or conditions outside the historical range will also inform how often these events can be expected in the future. Both the ensemble mean of the forecasts and the expected frequency of events can provide a baseline to anchor risk analysis given climate change. For example, in addition to showing a time series with respect to its historical value, it can also be shown with respect to the forecasted ensemble mean. We expect this project to provide a first attempt at incorporating risk analysis of environmental conditions fundamental to assess ecosystem status that incorporates vulnerability to climate change.

Deliverables: The project will result in three main products: i) a method to replicate time series of three modeled ecosystem indicators from hindcasts of the NEP5-NPZD (1970-2009); ii) three climate driven forecasts for each modeled ecosystem indicator for the period 2012-2035, and iii) Suggested improved indicator(s) with corresponding forecast time series.

The results will be summarized in a final report to the FATE program and presented at scientific conferences (including but not limited to the annual FATE meeting). Results will also be submitted for publication in a peer-reviewed publication (e.g. Marine Ecology Progress Series). Likewise, time series and results will be incorporated into the environmental assessment contained in the Ecosystem Considerations chapter produced annually by the AFSC for the North Pacific Fisheries Management Council (http://access.afsc.noaa.gov/reem/ecoweb/index.cfm). Suggestions to improve the ecosystem indicators will be presented to the eastern Bering Sea ecosystem team, as well as the Council's Bering Sea/Aleutian Islands Plan Team and Scientific and Statistical Committee, for their consideration and final decision on changes adopted.

References

Aydin, K., N. Bond, E.N. Curchitser, M.G.A. Gibson, K. Hedstrom, A.J. Hermann, E.Moffitt, J. Murphy, I. Ortiz, A. Punt, and M. Wang. Integrating data, fieldwork, and models into an ecosystem-level forecasting synthesis: the Forage-Euphausiid Abundance in Space and Time (FEAST) model of the Bering Sea Integrated Research Program. ICES CM 2010/L21 downloaded 07/02/2012 http://www.ices.dk/products/CMdocs/CM-2010/L/L2110.pdf

Coyle, K.O., B. Konara, A. Blanchard, R.C. Highsmith, J. Carroll, M. Carroll, S.G. Denisenko, and B.I. Sirenko. 2007. Potential effects of temperature on the benthic infaunal community on the southeastern Bering Sea shelf: Possible impacts of climate change. Deep Sea Research II 54: 2885-2905.

Curchitser, E. N., D. B. Haidvogel, A. J. Hermann, E. L. Dobbins, T. M. Powell, and A. Kaplan.2005. Multi-scale modeling of the North Pacific Ocean: Assessment and analysis of simulated basin-scale variability (1996–2003), Journal of Geophysical Research. , 110, C11021, doi:10.1029/2005JC002902.

Danielson, S., E. Curchitser, K. Hedstrom, T. Weingartner, and P. Stabeno. 2011. On ocean and sea ice modes of variability in the Bering Sea. Journal of Geophysical Research, 116 , C12034, doi:10.1029/2011JC007389.

Fulton, E.A., Smith, A.D.M. and A.E. Punt. 2004. Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science, 62: 540-551

Gibson, G.A. and Y.H. Spitz. 2011. Impacts of biological parameterization, initial conditions, and environmental forcing on parameter sensitivity and uncertainty in a marine ecosystem model for the Bering Sea. Journal of Marine Systems 88: 214-231.

Haynie, A.C. and L. Pfeiffer. 2012. Why economics matters for understanding the effects of climate change on fisheries. ICES Journal of Marine Science. doi: 10.1093/icesjms/fss021

Hermann, A. J., G.A. Gibson, N.A. Bond, E.N. Curchitser, K. Hedstrom, W. Cheng, M. Wang, P.J. Stabeno, L. Eisner, K.D. Cieciel. *In prep*. A multivariate analysis of observed and modeled biophysical variability on the Bering Sea shelf: multidecadal hindcasts (1970-2009) and forecasts (2010-2040).

Hollowed, A.B., K.Y. Aydin, T.E. Essington, J.N. Ianelli, B.A. Megrey, and A.E. Punt. 2011. Experience with quantitative ecosystem assessment tools in the northeast Pacific. Fish and Fisheries, 12:189-208.

Hollowed, A.B., S. Barbeaux, E.D. Cokelet, E. Farley, S. Kotwicki, P.H. Ressler, C. Spital, and C.D. Wilson. 2012. Deep Sea Research II 65-70:230-250.

Kotwicki, S., T. W. Buckley, T. Honkalehto, and G. Walters. 2005. Variation in the distribution of walleye pollock (*Theragra chalcogramma*) with temperature and implications for seasonal migration. Fishery Bulletin 103:574-587

Large, W.G., Yeager, S.G., 2008. The global climatology of an interannually varying air-sea 1009 flux data set, Clim. Dyn. 33, 341-364

Levin, P.S., M.J. Fogarty, S.A. Murawski and D. Fluharty. 2009. Integrated Ecosystem Assessments: Developing the Scientific Basis for Ecosystem-Based Management of the Ocean. PLoS Biol 7(1):e1000014. doi:10.1371/journal.pbio.1000014

Link, J.S., D. Yemane, L.J. Shannon, M. Coll, Y.J. Shin, L. Hill, and M.F. Borges. 2009. Relating marine ecosystem indicators to fishing and environmental drivers: an elucidation of contrasting responses. ICES Journal of Marine Science, 67:787-795.

Mordy, C, and M. Lomas, 2012. The impact of sea-ice on bottom-up and top-down controls of crustacean zooplankton and the mediation of carbon and energy flow in the eastern Bering Sea. Report of The Bering Sea Ecosystem Study (BEST) Synthesis Workshop, convened Feb 6-9, 2012 at The Bermuda Institute of Ocean Sciences (http://www.jisao.washington.edu/data/BEST-BSIERP).

Mueter, F.J. and M.A. Litzow. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecological Applications, 18: 309-320.

NSF. 2011. Award 1107250: Collaborative Research: Impact of sea-ice on bottom-up and top-down controls of crustacean zooplankton and the mediation of carbon and energy flow in the eastern Bering Sea.

Overland, J.E., M. Wang, K.R.Wood, D.B. Percival, and N. Bond. 2012. Recent cold and warm events in a 95-year context. Deep Sea Research II 65-70:6-13.

Saha, S. and coauthors, 2010. The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc. 91, 1015.1057. doi: 10.1175/2010BAMS3001.1

Spencer, P. D. 2008. Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. Fisheries Oceanography 17:396-410.

Stabeno, P.J., N. B. Kachel, S. E. Moore, J.M. Napp, M. Sigler, A. Yamaguchi, and A. Zerbini. 2012. Comparison of warm and cold years on the southeastern Bering Sea shelf and some implications for the ecosystem. Deep Sea Research II, 65-7-: 31-45.

Stabeno, P.J., J. Napp, C. Mordy, and T. Whitledge, 2010. Factors influencing physical structure and lower trophic levels of the eastern Bering Sea shelf in 2005: Sea ice, tides and winds. Progress in Oceanography, 85: 180–196.

Stabeno, P.J., N.A. Bond and S.A. Salo. 2007. On the recent warming of the southeastern Bering Sea shelf. Deep Sea Research II, 54: 2599-2618.

Stevenson, D.E. and R.R. Lauth. 2012. Latitudinal trends and temporal shifts in the catch composition of bottom trawls conducted on the eastern Bering Sea shelf. Deep Sea Research II 65-7-:251-259.

Wang, M., J.E. Overland, and P. Stabeno. 2012. Future climate of the Bering and Chukchi Seas projected by global climate models. Deep Sea Research II 65-70:46-57.

Wang, M., J.E. Overland and N. A. Bond. 2010. Climate projections for selected large marine ecosystems. Journal of Marine Systems, 79: 258-266.

Wiese, F.K., W.J. Wiseman Jr. and, T.I. Van Pelt. 2012. Bering Sea Linkages. Deep Sea Research II. 65-70:2-5.

Zador, S. (Ed). 2012. Ecosystem Considerations for 2012. Appendix C. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the erring Sea/Aleutian Islands Region. North Pacific Fishery Management Council. 254p. downloaded 08/10/2012 http://access.afsc.noaa.gov/reem/ecoweb/Eco2011.pdf