Title: Ichthyoplankton metrics as fishery-independent indicators of ecosystem change along the US west coast from California to Alaska

Lead Principal Investigator: Janet Duffy-Anderson
E-mail: Janet.Duffy-Anderson@noaa.gov; Ph: 206-526-6465

Lead Principal Investigator Institution:
Alaska Fisheries Science Center
7600 Sand Point Way NE
Seattle, WA 98115

Associated NMFS Fisheries Science Centers and Institutions: Southwest Fisheries Science Center, Northwest Fisheries Science Center, Scripps Institute of Oceanography (University of California San Diego)

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All Other Co-PIs and Institutions: J. Anthony Koslow (SIO/UCSD), Richard Brodeur (NWFSC), Mary Hunsicker (NWFSC), Sam McClatchie (SWFSC), Stephani Zador (AFSC), Steven Bograd (SWFSC)

Institutional breakdown of Year 1 budget:

AFSC $96,500

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Background

Ecological time series are critical to understanding and managing ocean ecosystem response to climate variability, climate change and other stressors. Although critical to the Integrated Ecosystem Assessment (IEA) process and to Ecosystem Based Fishery Management (EBFM), the development of ecological time series, in particular for fish communities, considerably lags that of physical and chemical time series in current ocean observation frameworks (Koslow & Couture 2013). However, NOAA has maintained an extensive network of ecological observations through ichthyoplankton survey programs at its regional laboratories: e.g. CalCOFI, EcoFOCI, the NH line and others (McClatchie et al. 2014). Larval abundance reflects spawning stock biomass (Moser and Watson 2006, Koslow et al. 2011), thus larval survey data constitute fishery-independent time series of marine fish communities from the Bering Sea and Gulf of Alaska to the southern edge of the California Current, providing a robust framework for evaluating west coast-wide, cross-ecosystem shifts that that may have occurred in response to climate variability and/or anthropogenic activities. Moreover, since fish larvae are part of the lower trophic community they respond rapidly to ecosystem shifts (Duffy-Anderson et al. 2006), so indices developed from ichthyoplankton time series have significant potential to be early harbingers of future changes.

Initially, ichthyoplankton collection programs focused on key commercial species (e.g. anchovy, sardine, walleye pollock and others), although quantitative, taxonomically-resolved data are obtained for a diverse array of non-commercial as well as commercial species of ecological importance in each region. Accordingly, it is possible to develop integrated biodiversity indices, as well as single species metrics, to evaluate change over time. Ichthyoplankton data sets are increasingly being analyzed for their wealth of information on the status of regional fish communities and the impacts on them of fishing, climate, and other factors (Hsieh et al. 2006, 2009, Boeing and Duffy-Anderson 2008, Brodeur et al. 2008, Doyle et al. 2009, Auth et al. 2011).

Recent analyses of the CalCOFI ichthyoplankton time series revealed dramatic changes over time in fish communities of the southern California Current Ecosystem (CCE). The dominant pattern (or principal component (PC)) in the CalCOFI data set revealed a coherent shift in the abundance of some 24 taxa of mesopelagic fishes, which was highly correlated with midwater oxygen concentrations. Since 2000, a period of reduced midwater oxygen and an expanded oxygen minimum zone (OMZ), their mean abundance was reduced by >60% (Koslow et al. 2011). Midwater oxygen concentrations are now widely reported to be declining in the global ocean, particularly in the North Pacific and other regions with significant OMZs (Emerson et al. 2004, Whitney et al. 2007, Stramma et al. 2008, Helm et al. 2011), and they are predicted to continue to decline due to global warming (Keeling et al. 2010).

The PC analysis also revealed that a broad suite of cool-water affinity fishes in the southern CC, including several of the most abundant taxa (e.g. northern anchovy, Pacific hake, and several rockfishes), have declined significantly since about 1969, leading to a 72% reduction in the overall abundance of larval fishes in the CalCOFI time series (Koslow et al. 2013, Koslow et al. in press). This pattern is correlated with warming near-surface temperatures and declining zooplankton displacement volume. Changes of this magnitude could have profound implications for the productivity of west coast marine ecosystems, and species complex indices (ex: cool water complex) can provide important metrics by which changes can be evaluated.

How widespread are these changes? One hypothesis is that these changes are largely limited to or amplified in the southern CC, because the region of core CalCOFI sampling off southern California is an ecotone, where fishes with cool-water and Transition Zone distributions mix with tropical/sub-tropical affinity species (Horn et al. 2006). Another is that changes are more widespread, occurring across LMEs and influencing ecosystem dynamics in the Gulf of Alaska, the Bering Sea, and beyond. This hypothesis is supported by the fact that ENSO events and shifts in the Pacific Decadal Oscillation (PDO) are basin-scale phenomena whose ecological impacts are typically manifest over extensive portions of the west coast of North America (Chelton et al. 1982, Hollowed et al. 1987, Hare and Mantua 2000). Many of the key taxa that have declined in the southern California Current are broadly distributed in the California Current (e.g. northern anchovy, Pacific sardine, Pacific hake, rockfishes (*Sebastes* spp.)), and some extend well beyond, such as various mesopelagics, e.g. the northern lampfish, *Stenobrachius leucopsarus*.

Studies from Alaska and the northern California Current also indicate that ichthyoplankton abundance is linked to large-scale ocean forcing, such as El Niño and warm/cool phases of the North Pacific (Boeing and Duffy-Anderson 2008, Brodeur et al. 2008, Auth et al. 2011, 2015). Clearly there is an urgent need to assess the extent and magnitude of potential shifts in west coast fish assemblages and to develop a set of regional indicators of climate impacts on them. This can be achieved by synthesizing, analyzing and comparing ichthyoplankton time series for the waters off Alaska (SE Bering Sea and Shelikof Strait, AFSC), and the Pacific Northwest (Newport Hyrdoline line and other regularly sampled transects, NWFSC), and California (CalCOFI, SWFSC). We believe a relatively small additional investment may yield a vastly improved understanding of the status of US west coast Large Marine Ecosystems (LMEs).

Approach

Our project will proceed, first, by assembling ichthyoplankton data sets from the Bering Sea (20 years), Gulf of Alaska (Shelikof Strait; 30+ years) and the northern and southern California Current (NH line 20 years, CalCOFI 63 years). These will then be analyzed both individually using standardized methods and comparatively to assess shared and unshared patterns of change in key species and assemblages, potential relationships with environmental drivers, and spatial-temporal scales of coherence among fish assemblages along the west coast of North America. We will then assess which populations/assemblages may serve as indicators of ecosystem status and the spatio-temporal scale of such indicators.

Several key hypotheses will be tested:

· H_o: Coast-wide shifts in ichthyoplankton community structure and abundance have occurred in response to changing ocean conditions

· H_o: Larval fishes along the west coast with cool-water affinities exhibit a decadal-scale decline at the southern edge and a possible increase at the northern end of their range, leading to the appearance of large-scale coherence along with a possible inverse response in Alaskan waters (Gulf of Alaska/Bering Sea) versus the California Current

· H_o: Multispecies complexes can be identified in each region to serve as indicators of biological impacts of changing ocean conditions (e.g. deoxygenation, warming).

The time series that will be used in the project are already available in databases either at the individual labs or on NOAA or other servers. The underlying NOAA programs (e.g. CalCOFI, EcoFOCI, Newport Hydroline line) are described in McClatchie et al. (2014). A postdoctoral research associate (National Research Council/TBN) will be hired to work collaboratively with the PIs and collaborators at all laboratories to assemble the data sets for comparative analysis and to carry out the analyses. This requires, for example, ensuring spatio-temporal consistency in sampling across years within a region, as well as consistent seasonality and habitat coverage (e.g. shelf/slope/offshore) for comparisons across regions. Physical oceanographic time series related to the El Niño Southern Oscillation (ENSO) cycle (the ONI), decadal basin-scale variability (the Pacific Decadal Oscillation, PDO, and North Pacific Gyre Oscillation, NPGO), and local oceanographic conditions (temperature, salinity, chlorophyll, and in many cases, zooplankton) are also available. There has been considerable development in recent years of improved measures of coastal and offshore upwelling, transport of the California Current and changes in water masses (e.g., dissolved oxygen content) within the California Current (Keister et al. 2011, Bograd et al. 2014, Jacox et al. 2015), which will be used in the project.

We propose to utilize varied approaches to data examination that will provide robust and independent quantitative analyses. First, traditional multivariate analyses, such as principal component analysis (PCA), have been widely used and are a powerful tool in reducing the dimensionality of these diverse ecosystems and revealing the importance of key multispecies patterns linked to ecosystem processes (Koslow et al. 2011, 2013, in press). Ordination (e.g. Non-metric Multidimensional Scaling, NMDS) and cluster analyses will also be carried out to assess shifts in community organization. Approaches will be similar to those used in Duffy-Anderson et al. (2006) to examine the impact of El Niño on larval fish assemblages. Appropriate forms of correlation, regression, and other analyses will be used to examine relationships between ecological and oceanographic time series, with significance levels corrected for autocorrelation in the time series (Pyper and Peterman 1998). Species groupings that exhibit the greatest sensitivity to various climate drivers (ENSO, deoxygenation, temperature) will be used as metrics to evaluate change across and within Large Marine Ecosystems.

Second, dynamic factor analysis (DFA) has been employed previously to detect common patterns in sets of time series data and to determine relationships between time series and explanatory variables (Zuur et al. 2003, Friedland and Hare 2007). DFA can be readily conducted in R using the Multivariate Auto-Regressive State Space (MARSS) package (Holmes et al. 2014) and complements the approaches described above. In particular, this class of model is useful for the examination of linear stochastic dynamic systems, allowing the user to fit time-varying models with covariate time-series data via maximum likelihood using an Expectation Maximization (EM) algorithm (Holmes et al. 2012, 2014; http://faculty.washington.edu/eeholmes/). Dynamic factors can be identified along with latent driving forces of the ecosystem, which can provide critical information on factors that exert disproportionate control on the system. DFA is presently being used to determine how observed multi-decadal, multi-trophic shifts in the Gulf of Alaska (Marshall et al., NWFSC; Hunsicker, Principal Investigator, Duffy-Anderson, collaborator) are related to fishing, climate change and the Exxon Valdez oil spill, of which ichthyoplankton time series data are one variable utilized in the model.

Finally, Random Forest and Gradient Forest Models (Brieman 2001, Cutler et al. 2007) are statistical models that show promise for these analyses as well, relying on nearest neighbor

predictors to improve performance. Random forest and gradient forest methods have been used previously to quantify the relative importance of selected environmental variables to the distribution of species in the Bering Sea, and to show shifts in species community structure along environmental gradients (Baker and Hollowed, 2014). By using an ensemble approach with packages that are readily available in R (Classification and Regression, CRAN) we can characterize the magnitude of change along environmental predictor gradients and identify critical values along the predictor gradients that correspond to threshold shifts in species composition.

Taken collectively, these approaches will offer redundant yet independent methods of examining and quantifying changes in ichthyoplankton communities along the US west coast. Patterns that are sufficiently robust to appear across approaches will be those identified as indicators of ecosystem change and pursued for development of metrics.

Benefits:

The proposal addresses several FATE Research priorities, as well as Fishery Science Center Annual Guidance Memos. First, the FATE goal to "*develop indices of environmental indicators to investigate specific mechanisms driving interactions between fisheries and climate*," will be addressed by identifying key species groupings (*harbinger complexes*; ex: mesopelagic fishes, cool water complexes, sentinel species for range expansion/contraction, ENSO-sensitive groupings) that provide robust indicators of environmental change. These harbinger complexes will contribute to improved management by enabling recruitment forecasting for species with heightened environmental sensitivities in the larval stage under various future climate scenarios. Research to elucidate impacts of climate change on fisheries and/or developing indicators of ecosystem change are specified as research priorities in the most recent Annual Guidance Memos from the relevant centers: SWFSC (FY16), AFSC (FY16), and NWFSC (FY15). The newly-developed harbinger complex indicators have application to NOAA's multipronged approach to broad EBFM goals through informing ongoing climate research (e.g., CLIM project) and Integrated Ecosystem Assessment and ecosystem status report efforts (e.g., Alaska's Ecosystem Considerations and the State of the California Current reports) of the three Centers. For example, indicators of lower trophic levels response to environmental forcing are of high priority for the California Current Integrated Ecosystem Assessment and Alaska's Ecosystem Consideration report, and could be readily incorporated for the annual review by the North Pacific Fisheries Management Council's Scientific and Statistical Committee.

Second, the FATE goal to "*develop spatial and/or temporal models that analyze climate and environmental variability*" will be addressed by developing a multivariate statistical approach (described above) that can be used to provide an up-to-date assessment of the status of fish communities along the west coast of North America in relation to climate: patterns of change, coherence between regions (Bering Sea, Gulf of Alaska, California Current) and sub-regions (north and south California Current), and relationships with local and large-scale ocean drivers. Once methods are developed they can readily be applied to long-term ichthyoplankton datasets in other large marine ecosystems (NEFSC, SEFSC, etc.). We will seek collaboration and dialogue with these scientists throughout this project as a first approach to building a nation-wide network of ichthyoplankton metrics that can be available to stakeholder and managers throughout the country. This process could readily begin through dialogue and interaction with

other representatives from other Centers that also utilize the Plankton Sorting and Identification Center in Szczecin, Poland (NEFSC and SEFSC) that have long time series of similarly-collected and sorted data.

Third, the FATE goal to "*develop, improve or augment indicators that could be used in ecosystem-based fishery management*," will be addressed by testing the feasibility of using ichthyoplankton taxa or groupings as key indicators of ecosystem status for use in ecosystem-based fisheries management. Interannual variations in ichthyoplankton biomass along the Newport Hydroline Line is presently used as a leading indicator of food conditions for juvenile salmon entering the ocean (Daly et al. 2013, McClatchie et al. 2014) and similar indices could be developed for other systems/species in the Northeast Pacific. Given that certain climate trends, such as deoxygenation and warming, are predicted to continue, a multivariate approach that can be used across ecosystems will provide an improved understanding of past fish community response to these trends and will provide predictions and hypotheses that can be tested with future data.

This project also addresses the Alaska Fisheries Science Center's FY16 research priority (3) *research on process studies linking recruitment of commercially important species to environmental change, including climate change*. This project will utilize AFSC time series data collected from process studies occurring over 30 years to inform Ecosystem Based Fishery Management (EBFM) and forecast population response to climate change. Further, the use of new and existing data to develop indicators that can be used *to assess ecosystem status and trends* and *provide scientific support for the implementation of EBFM* is a key component of the NWFSC Strategic Science Plan.

Deliverables:

Over the course of this project, we will deliver the following:

(1) summaries of oceanographic and ichthyoplankton indicators (species-specific, biodiversity, and species complexes) for the west coast of North America from the Bering Sea to California formatted to Integrated Ecosystem Assessments (IEA) standards and published on IEA websites;

(2) publication of ichthyoplankton data and indicators on the AFSC, NWFSC, and SWFSC web sites;

(3) presentations at FATE meetings, CalCOFI, PICES or other scientific conferences; and

(4) 2-4 manuscripts based on results and insights from comparative analysis of ichthyoplankton time series and ecosystem indicators in the context of oceanographic dynamics and climate forcing. Tentative topics include:

a. Methodology of ichthyoplankton indicator development
b. Ichthyoplankton biodiversity indicators as harbingers of climate shifts
c. Sentinel species abundance changes forecast coast-wide oceanographic shifts
d. Occurrences and range shifts of temperate species into subarctic marine systems

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