# NOAA - National Marine Fisheries Service <br> Fisheries and the Environment (FATE) <br> FY 2008 Annual Report <br> September 2008 

## Executive Summary

The Fisheries and the Environment (FATE) program is a research program that develops and evaluates ecological and oceanographic indicators to be used to advance an ecosystem approach to management by improving fishery stock assessments and integrated ecosystem assessments. This information is necessary to effectively adapt management to mitigate the ecological, social, and economic impacts of major shifts in the productivity of living marine resources.

Sufficient understanding of the influence of species interactions and their responses to environmental change is required to develop forecasts and assess the long-term impact of climate and fishing on marine ecosystems. The goal of the FATE program is to provide the information necessary to effectively forecast these changes in order to evaluate management strategies needed to sustain fisheries, while preserving ecosystem structure and function. In support of this goal, the FATE program was designed to accelerate the development of next generation decision analysis and forecasting tools. FATE is providing leading indicators of ecological and oceanographic change by supporting research on the functional relationships between environmental forcing, competition for prey, or predation on the growth, distribution or reproductive success of managed species. The ultimate measure of FATE success is the incorporation of indices and functional relationships in population dynamics models, ecosystem assessments, and evaluation of fishing and climate forcing on marine resources that can be used to inform mangers of the implications of their actions.

FATE supports applied science with a focus on ecosystem indicators and forecasting tools that can be utilized to proved advice to managers. FATE accomplishes this through a core team of scientists distributed among NMFS research centers and projects selected from an annual request for proposals. This report compiles the individual annual reports of the three full time FATE scientists and the fourteen projects that received funding in FY 2007 and conducted research through FY 2008. In addition, seven new projects received funding starting in FY 2008 as a result of the 2008 request for proposals. These seven projects did not submit an annual report for 2008, as they have just been initiated, but are listed at the back of this report.

More details on FATE and its products are available online at http://fate.nmfs.noaa.gov/

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## Project Title: PIFSC FATE FTE

Principal Investigator: Evan Howell

## RECENT INDICATORS:

## EOD TurtleWatch product (REVISED FOR 2008):

Background: The PIFSC TurtleWatch product is a map providing up-to-date information about the thermal habitat of loggerhead sea turtles in the Pacific Ocean north of the Hawaiian Islands. Distributed daily both electronically and in paper format to individuals and entities in the Hawaii Longline Fishing industry. This product is aimed to minimize bycatch of loggerhead turtles by the longline fishery by indicating the SST values where the highest probability of a loggerhead turtle interaction may take place.

Revision: This product was revised for the 2008 fishing season based on results from the first quarter of 2007. The 2007 TurtleWatch product recommended no placement of shallow sets in waters cooler than $18.5^{\circ} \mathrm{C}$. Based on the results from the 2007 season, there was no bycatch in waters cooler than $17.5^{\circ} \mathrm{C}$. Based on these new results and the historical SST values where loggerhead turtle interactions occurred, the new recommendation is to avoid the placement of shallow sets in waters between $17.5^{\circ}-18.5^{\circ} \mathrm{C}$. This information was distributed in the same formats as in 2007, yet additionally was delivered to fishers by GeoEye through their data distribution system.

The council in their SEIS presented the recommendation of cessation of shallow sets in the area demarcated by this product as a proposed scenario this year. Overall the WPRFMC has been very supportive of the use of the TurtleWatch product in future management decisions.

These results from 2007 were published in a special issue of Endangered Species Research on bycatch.

Modeling of the potential vulnerability of bigeye tuna in the Hawaii-based longline fishing grounds: Data from 29 Popup Archival Transmission tags attached to fishery landed bigeye tuna were used to model the potential vulnerability of these animals to deep-set longline fishing gear. Dive "types" were defined based on the recorded data for each daytime period for every animal. The probability of these dive types was then modeled using a GAM approach. The results of this model indicated that SST is the most important factor in describing the frequency of deep daytime behavior of bigeye tuna. These results were submitted as part of a larger body of work on dive behavior of bigeye tuna to Progress in Oceanography.

Indicator of trend of oligotrophic portion of subtropical gyres: The work on the time series of the area of each ocean's subtropical gyres that contain a chlorophyll concentration less than or equal $0.07 \mathrm{mg} \mathrm{Chl} a \mathrm{~m}^{-3}$ was updated and this work was published in GRL. These revisions in FY2008 were based on work that was completed in 2007 for the FATE program.

Indicator of altimetry conditions on Sablefish habitat off the northwestern US coast: This product is a time series of the monthly mean altimetry values in the latitudinal range $44 \mathrm{~N}-50 \mathrm{~N}$ spanning the area from the coastline to the 1000 m bathymetric contour. This product was conceived in 2007 and was continuously updated each month throughout the year. Work was completed to attempt to replace the currently used tide gauge data with this product in the sablefish assessment.

Indicator of diversity of functional phytoplankton groups in the North Pacific Ocean: This work is collaboration with Jeffrey Polovina that builds on the oligotrophic gyres paper. Here we are using time series of functional phytoplankton groups that are estimated using the PHYSAT model developed by Sevarine Alain in France. The goal of this project is to use these groups to assess variability in the functional groups and overall phytoplankton diversity over the last ten years in the North Pacific Ocean, with the idea that changes in these time series may be representative of a shift in habitat.

## FY2008 PUBLICATIONS:

Howell EA, DR Kobayashi, DM Parker, GH Balazs, and JJ Polovina. TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles Caretta caretta in the Hawaii-based pelagic longline fishery. Endang. Species Res. (2008) pp. 12

Howell EA, DR Hawn, and JJ Polovina. Spatiotemporal variability in bigeye tuna (Thunnus obesus) dive behavior in the central North Pacific Ocean. Submitted. Prog. in Oceanogr.

Polovina, JJ, EA Howell and M Abecassis. Ocean's least productive waters are expanding. Geo. Res. Lett. (2008) 35 (3) pp. 5

## FY2008 PRESENTATIONS

August 2008. EOD TurtleWatch: Hooked on Pixels! Applications of remotely-sensed data to current questions in fisheries oceanography. FATE Science Meeting, La Jolla, CA. Oral presentation

July 2008. Applications of remotely-sensed satellite data in fisheries oceanography. WPFRMC Regional Ecosystem Advisory Committee, Honolulu, HI. Oral presentation

July 2008. Applications of remotely-sensed satellite data in fisheries oceanography. Moana Lua High School Fisheries Management Class (Outreach presentation), Honolulu, HI. Oral presentation

May 2008. Spatiotemporal variability in bigeye tuna (Thunnus obesus) dive behavior in the central North Pacific Ocean. $58^{\text {th }}$ Annual Tuna Conference, Lake Arrowhead, CA. Oral presentation

May 2008. TurtleWatch. Loggerhead Turtle bycatch workshop, La Jolla, CA. Webinar presentation

December 2007. Vertical behavior and habitat estimates of bigeye tuna (Thunnus obesus) in the central North Pacific. $1^{\text {st }}$ Annual Cliotop Conference, La Paz, Mexico. Oral presentation

December 2007. TurtleWatch: A data product to aid in the bycatch reduction of loggerhead turtles (Caretta caretta) in the Hawaii-based pelagic longline fishery. WPRFMC Loggerhead Turtle Recovery Meeting, Honolulu, HI. Oral presentation

## Project Title: SWFSC-ERD FATE FTE

Principal Investigator: Andrew Leising
Since becoming one of the FATE-FTE's in fall of 2007, I have three projects I have worked on which are all FATE-relevant:

1) Copepod dormancy and population dynamics within the CA current, and the Gulf of Maine (this is a continuation of my collaboration in two separate GLOBEC funded projects, and a newly funded GLOBEC pan-regional project)
2) Feeding and reproductive rates of copepods in response to varying water column structure (this is part of an ongoing collaboration with UW and UMCES faculty, who are funded through an NSF grant; UW is seeking a no-cost extension for their further involvement)
3) The swimming and feeding response of copepods to microscale structure and chemical cues (this is part of a collaboration with faculty from Georgia Tech, who are funded through an NSF grant)

## Goals:

Overarching goals and objectives of the project.
Project 1) The overall goal of this project is to understand how dormancy in Calanus spp. is controlled, particularly with relevance to environmental variables. Once this is understood, modeling can be used to make improved hindcasts and predictions of copepod abundance and productivity. This information is critical for understanding how climate influences the productivity of copepods, and hence their availability as prey for higher trophic levels, such as small pelagics and the larvae of larger fish species. The first objective is to compile all observed data on Calanus marshallae and pacifcus (for the Pacific) and C.finmarchicus and C.helgolandicus (for the Atlantic) and relevant biophysical data for use in creating dormancy climatologies. The second objective is to use individual-based models to explore the hypothesized dormancy control mechanisms, and then to examine how climate variability can affect the target species.

Project 2) The goal of this project is to understand how vertical water column structure affects the feeding and reproductive success of copepods over short (one day) time periods, and the resulting availability of the copepods as prey to surface feeding fish species. The first objective of this study is to describe the observed swimming and feeding behavior of target copepods species as they forage within natural field situations from different seasons (thus different water column structures), and then develop individual-based models of the behavior. The second objective is to use the developed IBM's to explore how regional scale and long-term changes in water column structure may affect the reproductive success and prey availability of copepods to higher trophic levels throughout the CCS.

Project 3) The overall goal of this project is to understand how microscale gradients in biophysical water column structure (i.e. chemical gradients, turbulence, shear, etc.) affect the short term feeding and swimming responses of copepods over brief (hours) timescales. The objectives
of this study are first, to observe the responses of target copepod species to microscale gradients of biophysical properties, second, to develop models of these behaviors, and third, to use models to compare predicted and observed field distributions of copepods, during which the model will be used to further predict reproductive success, and spatial location of the copepods, with relevance to their proximity to the feeding areas of larval and small pelagic fish.

## Approach:

Description of the work that was performed.
Project 1) During 2007-2008, I completed the compilation of the C. pacificus/C. marshallae dormancy climatologies and relevant physical data. I have also finalized the choice of parameters for the copepod IBM into a "best" set, which enables simulations that adequately mimic the observational data. Many of these physiological parameters are not well constrained by any data, so this involved considerable model tweaking to fit the abundance and relative stage distribution data. Additionally, a new component was added to the IBM model previously developed; the ability to make "inverse" backcalculations, i.e. given a set of observed abundances of various copepod life stages, the model can calculate the probable time each stage was spawned, taking into account the observed temperature and prey availability in the region where the copepods were located, for the time period between spawning and when they were sampled. This method is detailed and used in the paper by Johnson et al. 2008, of which I am a coauthor. Two additional manuscripts describing this work are in prep for submission by the end of 2008; the first details the copepod observational climatologies, and the second presents modeling results and impacts of dormancy on population dynamics of the pacific species group.

Project 2) The previously developed IBM of copepod short-term foraging behavior was updated to include a realistic temperature and ingestion rate dependent gut clearance and egestion mechanism. Also, the model was adapted to be able to calculate a temperature and ingestion dependent egg production rates for the simulated copepods. Lastly, the model was updated to allow forcing from observational CTD/bottle cast data. Given these updates, the model was then forced with every single CTD/bottle cast profile taken during the CALCOFI program from 19842007; a total of 7646 model runs. The model has also been run for every CTD/bottle cast taken from the GLOBEC LTOP and PROCESS cruises conducted in the coastal Oregon region from 1997-2004, for a total of 591 additional runs. In order to validate the results of this model, I also digitized the egg production rate data from Mullin, 1991 (CALFOCI report), and have compared it to the relevant IBM runs for the same cruises and stations (this covers $\sim 36$ stations per cruise, for 8 cruises over 3 years). Lastly, I was coauthor on a paper submitted to L+O methods detailing the methods of our background field work on this project; this paper includes data supporting our hypothesis concerning the foraging behavior of copepods with regards to water column structure, and as such, forms the theoretical background behind the behaviors implemented in the IBM.

Project 3) For this project, a new IBM of copepod foraging and response to stimuli was developed. What makes this model a new advancement, is that it is fully 3D, and includes a more detailed suite of possible copepod behaviors, and the ability to include a wider range of forcing (e.g. shear; chemical cues etc.) for the copepods to react to. The model is also fully scalable, e.g. it can be used to mimic the exact properties used in the laboratory experiments that
will be conducted at Georgia Tech in small 1-2 m sized tanks, up to exploration of copepod movements within the field, on scales of tens of meters.

## Work Completed:

Summary of progress, including results obtained / products developed, and their relationship to the goals of the project. If problems developed which resulted in unexpected results, they should be discussed.

Project 1) Significant results of this work include the further refinement of our hypotheses concerning the factors that control dormancy in Calanus spp. Specifically, we hypothesize that copepods enter dormancy after accumulating a certain threshold concentration of lipid stores (it is still unclear if this threshold is an absolute amount, or a relative amount based on the size of the copepod), and that the length of dormancy is controlled by the usage of this lipid store as modified by the temperature at the location of the copepod. We also hypothesize that there is an additional endogenous timer that acts as an absolute "alarm" and can wake copepods from dormancy regardless of relative lipid content once they have reached a certain developmental status within their dormant stage. Given this, we propose that there is a critical environmental "window" that must include a critical combination of temperatures and prey levels which either allows or does not allow copepods to enter the dormant stage. Thus this window is directly (and non-linearly) related to climate variability. We have concluded that these hypotheses, so far, are the best explanation of our compiled observational data. We have also "debunked" the previously supposed null hypotheses that either light levels or an avoidance of high summer/fall temperatures are factors controlling dormancy.

Given our dormancy control hypotheses are correct, IBM modeling has shown several interesting results. First, we have seen that earlier spring transitions to upwelling result in much larger spring and summer copepod biomasses and higher productivity. Part of this results from the ability of the copepods to add an additional generation per year, due to their early start. Vice versa, late spring transitions are very deleterious to the population, as a large portion of the adults may wake from dormancy too early to find available food, and possibly die before reproducing. Also, this modeling work has shown that large-scale effects like El nino may not always impact the copepods immediately, but can have impacts lagged as much as a year. Lastly, given a return to good conditions (high phytoplankton abundances, and normal or early spring transitions) the populations appear to be able to undergo rapid recoveries from previous poor states. These features of the population dynamics of these species can not be reproduced from non-IBM models or models that do not include the dormancy control, since they have no way for the population to respond properly to environmental variability, and the use of the dormant stage as a refuge from poor conditions.

Project 2) Our work on this project has supported our earlier hypothesis that certain copepod species conduct what we call a "foray" foraging strategy. In this strategy, copepods swim in regions of high food levels within the water column, feed for a certain period, and then either sink or actively swim (it is not clear yet which is the case, or a combination) to deeper layers containing less food. Theoretical work has shown that this kind of behavior has the advantage of likely increasing retention within regions of better food resources, while also allowing for maximum ingestion rates, and lowered risk of predation to predators (for those predators which are confined mainly to the surface mixed layer; this includes many small pelagic fish species,
and the larvae of many larger fish species). Using the "foray" behavior, the IBM model is able to produce egg production rates that are very highly correlated ( $\mathrm{p}<0.01$ ) with the observed egg production rates obtained by Mullin, 1991; further validating the model and therefore our foray hypothesis. Further analysis of the CALCOFI and other dataset forced runs of this model should therefore enable classification of copepod egg production "hot spots" both spatially and seasonally, from throughout the CCS.

Project 3) This project is still in its development stage, so there are no results as yet, and is limited to the work as described in the above section.

Overall project products:
All three of these projects have resulted in the development of new copepod IBM's. Further, all three of the models share the facet that, while written in MATLAB, they include graphical user interfaces (GUI's), and thus can be used by anyone without having to have any knowledge of how the programs are written or coded (all that is required is the MATLAB program, and knowledge of how to start a matlab script from the command line; everything else is taken care of by the GUI). Thus, others can use these models for exploring how copepods react to environmental conditions, across a multitude of scales (e.g. the dormancy model runs for 10 's of years; the foray model runs for one day; the 3D model runs for seconds to hours). As such, these models form a series of products that are available for use by others, and require no knowledge of computer programming to run.

## Applications:

Describe how results are being used in stock assessments or otherwise benefiting living marine resource management.

All three of these projects carry the common theme of working to improve our knowledge, in a mechanistic-based way, of the responses of copepods to physical and biological variability within their environment. The projects and resulting models span scales and behaviors that act from seconds and mm's to decades and hundreds of meters. The goal is to improve our ability to successfully model the population dynamics of these key species. Copepods are major consumers of primary production, and are also critical prey items for larval fish and small pelagics. As such, they are a key component in understanding marine ecosystems, particularly in response to climate variability. It is only through the use of these mechanistic-based models that there is hope of being able to adequately understand how these species will respond to climate change. These projects' products include the development of GUI-based models, which can be used as tools for both prediction and index development. Particularly, once fully validated, these models will be used to create indices of copepod egg production and population abundances that can be used for coupling to higher trophic level or stock assessment models, or for other management purposes, including IEAs. Specifically, the model developed in Project 1 can be used to provide long-term hindcasts and spatially specific indices of the population abundance of two key indicator species (the warm-condition indicator C. pacificus, and the cold-condition indicator C. marshallae). The model developed in project 2 will provide a potential eggproduction index that also spans the entire spatial and temporal range of the CALCOFI program, and can eventually be set up in an operational mode to compliment current CALFOCI sampling.

Models $2+3$ additionally provide a mechanism to produce a "prey susceptibility" index, that is, it is not an index of prey abundance, but an index of what percentage of the copepod population would be located spatially (in this case the vertical dimension) within the range of surface-mixed-layer restricted foragers, such as the larvae of many fish species, and small pelagic fishes, which is an advance over other biomass-only indices. Lastly, because copepods are such key species, both as prey for higher trophic levels, and as consumers of primary production, the knowledge gained through these projects of how these species respond mechanistically to the bio-physical environment should prove valuable for describing the current state of these ecosystems when preparing IEA's for the various regions.

## Publications/Presentations/Webpages:

Project 1) Johnson, C.L., Leising, A.W., Runge, J.A., Head, E.J.S., Pepin, P., Plourde, S., and Durbin, E.G. 2008. Characteristics of Calanus finmarchicus dormancy patterns in the Northwest Atlantic. ICES, J. Mar. Sci, 65:339-350.

Two additional manuscripts:
Effects of climate variability on dormancy and population dynamics of Calanus pacificus and Calanus marshallae within the California current, I: An inter-regional data comparison. Andrew W. Leising, Cindy Bessey, Catherine Johnson, Jeffrey Runge, William Peterson, Moira Galbraith, and Dave Mackas

Effects of climate variability on dormancy and population dynamics of Calanus pacificus and Calanus marshallae within the California current, II: application of an individual-based model. Andrew W. Leising, Catherine Johnson, and Jeffrey Runge.

Have been written and are currently awaiting review by the cast of authors before being submitted for publication. We anticipate submission by the end of 2008.

Project 2) Pierson, J.J., Frost, B.W., Thoreson, D., Leising, A.W., Postel, J.R., and Rasmussen, M. 2008. Trapping migrating zooplankton. Submitted to Limnology and Oceanography, Methods.

We anticipate the submission of two additional manuscripts, one with further results from our observational work, and some limited modeling concerning the impacts of the observed behaviors, and the second manuscript will detail the large scale application of the model to the calcofi and other data sets, including a comparison with the Mullin, 1991 egg production data, and predictions concerning the effects of spatial and temporal climate variability on copepod egg production rates.

Project 3) no publications or presentations to date.

## Project Title: SWFSC-FRD FATE FTE

Principal Investigator: Sam McClatchie

## Goals:

Work in 2008 focused on the following objectives:

- Derive and distribute indices of the area, range, and environmental quality of Coastal Pelagic Species spawning habitat in the California Current, for use in stock assessments (see publication 1)
- Deliver to the Pacific Fisheries Management Council and SWFSC Ecosystem Research Division a refined definition of sardine actual spawning habitat in the California Current, for improved management and conservation (see publication 1).
- Complete the third U.S. West Coast-wide Pelagic Ecosystem Survey (Chief Scientist)(see publication 6).
- Contribute to the CalCOFI research community (see publication 2)
- Contribute as a fisheries oceanographer to problems of concern to the small pelagics and large pelagics research groups at the SWFSC (see publications 3 \& 4).
- Contribute to reports requested by NOAA Headquarters (see publication 5).


## Work Completed:

1. The U.S. West Coast-wide Pelagic Ecosystem Survey was managed efficiently and completed fieldwork on August 20th. Both April and July/ August surveys were completed successfully.
2. The State of the California Current report was delivered on time in collaboration with SIO.
3. Considerable progress was made using the full 50 year SWFSC and SIO CalCOFI databases to define the parameters describing sardine and anchovy sardine habitat.
4. Two papers addressing topical issues in the California Current Ecosystem (Humboldt squid and oxygen trends) were completed.
5. A postdoctoral fellow was hired under the successful IOOS RA grant (PIs from SWFSC, SIO and UCLA).
6. The postdoc and SMcC made substantial progress on developing a set of convenience functions to facilitate analysis of the CalCOFI datasets using the R statistical language.
7. A visiting scientist from Japan began a two-year sabbatical in the fisheries oceanography laboratory comparing CalCOFI with Japanese long-term ichthyoplankton datasets.
8. Collaborative research grant applications were submitted to FATE (as PI), NASA, and CAMEO (both as a CI) in the last 12 months.
9. Numerous articles were reviewed for journals (including ICES Journal of Marine Science, Limnology and Oceanography, Progress in Oceanography, \& CalCOFI Reports).
10. Contributions to the Annual Science Plan, and to NMFS climate-related documents were done.
11. Papers were presented at several conferences, and meetings of working groups.

## Applications:

None of the results are yet being used in stock assessment. The procedures for the sardine assessment are fixed for 2008/ 2009, and a consultative process would be required to modify the assessment in subsequent years (pers. comm. Kevin Hill, SWFSC).

## Publications/Presentations/Webpages

1. McClatchie S, Lo N, Bograd S, Charter R (sub judis) Changes in the distribution of sardine spawning off California over 50 years. Limnology and Oceanography.
2. McClatchie S, Goericke R, Koslow AJ and 21 others (in press, 2008) The state of the California Current, 2007 - 2008: La Niña conditions and their effects on the ecosystem. CalCOFI Reports 49.
3. Vetter R, Kohin S, Preti A, McClatchie S, Dewar H (in press, 2008) Predator interactions and niche overlap between mako shark, Isurus oxyrichus, and jumbo squid, Dosidocus gigas, in the California Current. CaICOFI Reports 49.
4. McClatchie S, Goericke R, Cosgrove R, Vetter RD (submitted) Oxygen in the Southern California Bight: multidecadal trends, impact of El Niño, and implications for demersal fisheries. PNAS.
5. McClatchie S, Kohin S, Dewar H, Howell E (in press) Effects of climate change on North Pacific Highly Migratory Species. pp. 92-105 In Osgood, K. E. (editor). 2008. Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-89, 118p.
6. McClatchie S, Charter R, Demer D, Guy T, Hill K, Jahncke J, Lo NCH, Macewicz B, Sydeman W, Zamon J (in prep) Report on the NMFS California Current Ecosystem Survey (CCES) between San Diego, California and Cape Flattery, Washington in April and July/ August 2008.

06-07
Project Title: Long-term relationships among climate, somatic growth, and recruitment in Acadian redfish and the implications for stock assessment.

Principal Investigators: Bryan Black, George Boehlert, Oregon State University, Newport, Oregon. Ralph Mayo, Jay Burnett, NOAA/NMFS Northeast Fisheries Science Center

## Goals:

Environmental variability strongly affects fish growth and recruitment patterns, yet relationships among these variables are still poorly quantified for many species. Such studies would require high quality, long-term time series, which are often lacking, particularly for fish recruitment and growth. To address this problem, we are developing a high-resolution chronology for Acadian redfish (Sebastes fasciatus) in the northwest Atlantic using ring widths of otolith growth increments. Acadian redfish are sufficiently long-lived to construct a chronology several decades in length, and to apply dendrochronology (tree ring) techniques for data quality control and chronology construction. In particular, we are applying the tree-ring dating control technique of crossdating to statistically ensure that all growth increments are assigned the correct calendar year. The final chronology will be used to i) place current growth trends in the context of the past ii) determine the environmental variables that most strongly affect Acadian rockfish growth iii) relate the biochronology, environmental variables with recruitment data, iv) identify any compensatory growth following exploitation, and v) provide a novel method of age validation with annual precision for Acadian redfish. This approach will provide valuable ecological data for Acadian redfish, which can be used to augment current stock assessment procedures.

## Approach:

Archived Acadian redfish otoliths were available from the present back to the late 1960s. Given the longevity of approximately 50 years, we should be able to construct a rockfish chronology that spans several decades of the $20^{\text {th }}$ century. Otoliths will be thin-sectioned along a dorsal-ventral axis to 0.5 mm thickness, mounted on slides, and polished with increasingly fine lapping film. Once prepared, we will apply the dendrochronology technique of crossdating to ensure that all growth increments are assigned the correct calendar year. The procedure is based on the principles that at least one climatic variable limits growth, and that climate fluctuates over time. Under these conditions, climatic variability induces synchronous growth patterns in all individuals within a given region. These synchronous growth patterns, much like bar codes, can then be matched among all individuals to verify that all growth increments have been identified. When all growth increments are accounted for, growth pattern 'bar codes' will align among all samples. If the growth pattern, or bar code, of one individual is shifted by a year in comparison to the other samples, the point at which the shift occurs indicates a potential error where a growth increment has been missed or falsely added. A point that should be emphasized is that crossdating begins at the most recently formed growth increment that is known to correspond with the calendar year of collection (death) and proceeds toward the center. From this growth increment of known calendar year, growth patterns are crossmatched back in time, starting at the outermost ring and using the common climate growth pattern to establish the calendar year of successively earlier growth increments.

After visual crossdating, growth increments will be measured using the program ImagePro Plus v. 5.0 (Media Cybernetics, Silver Spring, MD). Increments will be measured along a continuous axis, oriented perpendicular to the direction of growth and extending from the outermost to innermost growth increment on the dorsal half of the otolith. Visual crossdating will then be statistically validated by cross-correlating the high-frequency climate signal among all samples. The first step in this process will be to isolate climate-induced growth patterns from all other influences on the growth increment width. Other factors that may affect increment width include age, vigor, physiological and developmental status of each rockfish, and any artifacts of otolith preparation. In tree rings and also otoliths, climate is unique from all other influences on ring width (age, vigor, etc.) in that it can induce high frequency (year-to-year) variation in growth increments (see Black et al. 2005, Canadian Journal of Fisheries and Aquatic Sciences. 62:2277-2284). In contrast, age and developmental effects induce long-term variations that last several years. Long-term effects are removed by detrending, in which a mathematical function that models long-term trends is fit to each measurement time series. Each value of the measurement time series is divided by the value predicted by the function, thereby removing the age-related trend as well as any vigor effects, and equally weighting each time series to a mean of one. Once the detrending is complete, each standardized time series will be correlated with the average of all other standardized time series. This process will be repeated for all samples. To facilitate finding potential errors, samples will be lagged by plus and minus zero to ten years. If a lagged specimen correlates more strongly with the growth patterns of all other samples, the number of lags indicates the number of rings missed or falsely added. All aspects of statistical verification of crossdating will be conducted using COFECHA, available at http://www.ltrr.arizona.edu/software.html .

Crossdated otolith measurements will then be used to develop a population-wide master growth chronology. In this step, detrended measurement time series will be averaged into a master chronology, which represents population-wide growth. We will explore a variety of detrending options (cubic splines, negative exponential curves) to determine the one that preserves the most climatically induced variance. Estimates of chronology precision and fidelity will include the average interseries correlation coefficient and the Expressed Population Signal, which both quantify the strength of the climate signal among all samples. These calculations will help us to determine the minimum sample depth for a valid chronology and the earliest year at which the chronology is valid. All chronology development will be conducted using the program ARSTAN available at http://www.ldeo.columbia.edu/res/fac/trl/public/publicSoftware.html . Once developed, the chronology will then be related to local ocean variables such as sea surface temperature, sea level pressure, and upwelling as well as basin-wide ocean variables such as the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. The master chronology will be correlated with the monthly averages of each ocean variable to determine the seasons in which ocean variability has the most impact on Acadian rockfish growth. For example, splitnose rockfish in the northeast Pacific exhibit very strong correlations with winter and early spring ocean conditions, but is largely unaffected by variability in the summer months. We will also apply wavelet analysis in order to determine the dominant frequencies of ocean variability over the length of the chronology. Dominant frequencies in the chronology can be compared to the dominant frequencies of such ocean oscillations as the NAO and AMO to identify the degree to which they coincide. Finally, the master chronology will be compared to catch data and recruitment data to identify growth patterns that precede years of good (or poor) harvest years or
recruitment numbers. We will also investigate the possibility of compensatory growth, which will likely be a sustained growth increase that follows population reduction and is not readily explained by environmental variability. A variety of detrending options and percent-growth change calculations can be used to identify these growth changes.

## Work Completed:

To begin this project, we focused on the northeast region of the Gulf of Maine, which we though should be sufficiently homogenous that redfish would share common patterns of growth, allowing for crossdating. We retrieved 169 redfish otoliths from fish at least 20 years in age from archives at the NE Center in Woods Hole (Figure 1). The otoliths we selected were collected between 1975 and 2000, allowing us a wide window of dates to construct the longest possible chronology. Average depth of collected otoliths was 220 m , average fish length was 35.6 cm , and mean age was 29 years old. Otoloth thin sections (thin-sectioned along a dorsalventral axis to 0.5 mm thickness) were mounted on slides, very carefully ground to a thickness that allowed for maximum resolution of growth increments, and finely polished with 30 micron lapping film. Once otolith thin sections were prepared, we experimented with a variety of lighting settings and found that transmitted light provided the best contrast. Of the original 169 otoliths, approximately 100 were of sufficient clarity for the next level of analysis. We maintained high standards for clarity so measurement error would be minimized in the final chronology.


Figure 1. Sampling locations for Acadian redfish.
In the process of crossdating, we found that the samples exhibited a high degree of synchronous growth, consistent with the levels observed in developing rockfish chronologies in the

North Pacific. Clarity of the otoliths is also comparable to what we have found in Pacific rockfish. In particular, a narrow 1983, 1977, 1970, and 1965 as well as a wide 1984, 1979, and 1963 aided in crossdating and assigning the correct calendar year to each growth increment. We did find a very subtle difference in the growth patterns in those individuals obtained from the southwestern portion of the study area. The most conspicuous characteristic of these specimens was a less pronounced 1979 signature year and a somewhat wider 1984 and 1985. These differences were minor, and not strong enough to yield any statistical differences from the larger population. For this reason, all samples were pooled into a single master chronology for the region.

A statistical check of crossdating in COFECHA revealed no errors in assigning the correct calendar years to each growth increment. Once a subset of the samples had been crossdated, growth increments were measured in Image Pro v. 6.1. Measurements were then detreded with negative exponential functions to preserve as much low-frequency variability as possible, and detrended measurements were averaged into a preliminary master chronology spanning 1958 through 2001 (Figure 2). The chronology shows considerable year-to year variability, and also includes longer-term trends (Figure 2). One important feature of this chronology is an increase in variance over time. Part of this phenomenon can be explained by relatively low sample size in the most recent decade, but to at least some extent, growth in this population does appear to be fluctuating to a greater degree. The increased variability in recent years is also captured in a wavelet analysis, which shows significant oscillations on four to eight year timescale from approximately 1985 to 2000 (Figure 3). Thus, these oscillations appear to be limited to the most recent half of the chronology.


Figure 2. Preliminary Acadian redfish master chronology.


Figure 3. Wavelet power spectrum analysis of the Acadian redfish preliminary chronology. Significant periodicities ( $p<0.10$ ) in comparison to red noise processes are outlined in black. The cone of influence where edge effects may be important is indicated by crosshatching.

The preliminary master chronology was related to monthly averages of sea surface temperatures obtained from COADS, the Northern Oscillation Index, and the Atlantic Multidecadal Oscillation. Correlations between the master chronology and sea surface temperatures and also the Northern Oscillation Index were weak. But the chronology did show strongly negative correlations with the Atlantic Multidecadal Oscillation, particularly during the late spring and summer (Figure 4). This relationship makes sense considering that these Acadian redfish were caught at the southern portion of the species' range. A warm phase of the Multidecadal Oscillation is therefore likely to stress the fish and negatively impact growth. Sea surface temperatures do not appear to capture the same environmental variability as the Atlantic Multidecadal Oscillation in this region, considering the poor correlations between Acadian redfish and temperature data. This is not surprising considering that the Atlantic Multidecadal Oscillation likely integrates a range of oceanographic variables in addition to sea surface temperature, and this more multidimensional perspective may better capture ocean variability important to redfish growth.


Figure 4. Correlations between the Acadian redfish master chronology and monthly averages of the Atlantic Multidecadal Oscillation.

Recruitment data for Acadian redfish in the Gulf of Maine, obtained from the NEFSC Status of Fishery Resources off the Northeastern US webpage at http://www.nefsc.noaa.gov/sos/spsyn/pg/redfish/ show that recruitment patterns in the Gulf of Maine are highly variable over time, often varying by an order of magnitude (Figure 5). For example, the years 1971 and 1992 were particularly strong for recruitment. There are also some longer-term trends with particularly low levels of recruitment from 1965 through 1990 (Figure 5).


Figure 5. Recruitment index of Acadian redfish in the Gulf of Maine and Georges Banks. Estimated number of year-1 recruits, in millions.

Considering the range of variability in recruitment, climate may have some degree of influence as it does in the case of growth. When the raw data were compared against climate variables (NAO, AMO, SST), we could find no significant linear relationships. However, when the recruitment data were log-transformed, they improved substantially, particularly with the Atlantic Multidecadal Oscillation (Figure 6). Recruitment data are often thought to be lognormal in distribution, and only by transforming them did we find highly significant correlations with the environment. As in the master growth chronologies, the only variable that significantly related was the AMO. Also, correlations were only significant when the recruitment data were lagged by a year such that the recruitment index became an indicator of year-0 redfish abundance rather than year- 1 , bringing the data into temporal alignment with the environmental variables. An interesting finding is that the correlations with AMO were all positive, opposite that of the master chronology, which negatively correlated with the AMO (Figures 4, 6). Thus, warm ocean conditions as captured by the AMO appear to favor successful recruitment, but cool conditions favor growth.


Figure 6. Correlations between the log transformed recruitment index, lagged by one year to year-0, and monthly averages of the Atlantic Multidecadal Oscillation.

Strong relationships with the AMO suggest that recruitment and the Acadian redfish master chronology are related, and that they should inversely relate to one another. Indeed, when log-transformed recruitment is compared to the master chronology, the relationship is significant and negative (Figure 7). A significant relationship only occurs when the recruitment index is lagged by one year such that recruitment at year 0 (rather than recruitment at year 1 ) is compared with the master chronology. The mechanism behind this negative relationship will require more investigation. Perhaps this negative relationship is a consequence of adults diverting energy from growth to reproduction, resulting in narrow growth increments during years of robust recruitment. Alternatively, recruitment and growth may be more closely connected to the physical environment. Thus, conditions that favor somatic growth don't favor recruitment, and vice versa. Ultimately, however this study demonstrates that growth, recruitment, and climate are related in this species, made possible through the time series generated by otolith growth increment analysis and unique long-term recruitment history available for this species.


Figure 7. Relationship between the Acadian redfish master chronology and recruitment.

This project is still active and we continue to additional samples will be added to the master chronology. Samples are particularly difficult to find that represent the most recent ten to fifteen years. Older fish that have lived through the 2000s are very few, but we are continuing to search for more to increase sample size and the quality of the chronology over the most recent decade. We are also targeting as many additional fish as possible from the western portion of the study area to better quantify the weak gradient in growth pattern we noticed in the original otolith sample set.

## Applications:

The crossdated chronology will have several applications related to fishery management:

1. The master chronology will serve as an age validation tool, which could be used for establishing highly accurate recruitment histories. Once the final chronology is complete, additional fish caught in the region may be crossdated against it. In the process of crossdating the correct calendar year may be assigned to each growth increment, including the innermost increment formed at the year of birth, thereby establishing an exact age (see Black et al. 2005, Canadian Journal of Fisheries and Aquatic Sciences. 62:2277-2284). Otoliths validated by crossdating can also be used for training tools for new age readers.
2. The chronology provides long-term perspectives on growth of the Acadian redfish. No compensatory growth from over-fishing is immediately apparent, nor are there dramatic changes in growth in the recent era.
3. The chronology quantifies the effects of climate variability on growth, which are considerable. The preliminary chronology indicated that the Atlantic Multidecadal Oscillation clearly has a strong influence on the growth of Acadian redfish. Reduced
growth can be expected during warm phases of the AMO, which is information that could be incorporated into stock assessments. Relationships between climate and growth will be better quantified once the final chronologies are complete.
4. Recruitment appears to be strongly influenced by climate variability. For Acadian redfish, recruitment is associated with cool phases of the Atlantic Multidecadal Oscillation. Such information will be of use to fishery managers, helping to account for recruitment variability over time.
5. The fact that somatic growth and recruitment are interrelated to one another as well as to climate underscores the sensitivity of this species to environmental variability. Climate should be carefully considered in management of this species, and interpreting, and potentially forecasting, the dynamics of the fishery.

## Publications/Presentations/Webpages:

The results of this study and other FATE-related studies have been the focus of the following presentations over the past year.

Presentations by BA Black:
Fisheries and the Environment Annual Conference. August, 2008. La Jolla, CA.
Relationships among growth, recruitment, and climate in rockfish from the Gulf of Maine and Gulf of Mexico
Keynote address, The First American Dendrochronology Conference, June 2008. Vancouver, BC. State of the Science: Sclerochronology: Application of tree-ring techniques in marine and freshwater ecosystems
NOAA National Marine Fisheries Service, Southeast Fisheries Science Center, April 2008. Panama City, FL. Growth increment analysis as a tool for comparing diverse taxa and ecosystems in the Pacific Northwest.
NOAA National Marine Fisheries Service, Alaska Fisheries Science Center, March 2008. Seattle, WA. Growth increment analysis as a tool for comparing diverse taxa and ecosystems in the Pacific Northwest.
15 ${ }^{\text {th }}$ Western Groundfish Conference, February 2008. Spatial and temporal variability in growth of yelloweye rockfish in the northeast Pacific

The following FATE-related manuscript is in press:
BA Black, GW Boehlert, and MM Yoklavich. 2008. Establishing climate-growth relationships for yelloweye rockfish in the northeast Pacific using a dendrochronologial approach. Fisheries Oceanography In press

The following manuscript was inspired by FATE research in rockfish. Here we have applied the tree-ring technique of crossdating to generate highly accurate age data for Pacific geoduck.

BA. Black, D Gillespie, SE MacLellan, and CM. Hand. 2008. Establishing highly accurate production-age data using the tree-ring technique of crossdating: a case study for Pacific geoduck (Panopea abrupta). Canadian Journal of Fisheries and Aquatic Sciences In press.

The following publication, which quantifies the relationship between growth rate and lifespan (i.e. within species slower-growing individuals live longer) was inspired by FATE-research. This growth and lifespan relationship is a concern in fisheries, and I took this idea and applied it to trees, for which there is a much larger growth-increment database.

BA Black, JJ Colbert, and N Pederson. 2008. Relationships between lifespan and radial growth rate within North American tree species. Ecoscience. In Press 15(3), September 2008.

The following FATE-related publication is in review
BA Black. Climate-driven linkages between marine and terrestrial ecosystems in western North America. Marine Ecology - Progress Series

## 06-13

Project Title: Developing quantitative tools to forecast the effects of climate variability on the population dynamics of Pacific salmon

## Principal Investigators

Mark D. Scheuerell (NMFS), Richard W. Zabel (NMFS), Nathan J. Mantua (UW)

## Goals

Researchers can improve stock assessments by incorporating data on the size and age structure of fish populations (Quinn and Deriso 1999). For Pacific salmon, data on the abundance and estimated survival rates for various life stages has substantially improved our ability to detect climate effects when compared to simple metrics of overall production such as recruits per spawner (e.g., Logerwell and others 2003; Scheuerell and Williams 2005; Crozier and Zabel 2006). By incorporating the effect of climate variability on specific life stages, we can begin to assess its overall impact on stock performance in a proactive manner, which will aid efforts to develop sustainable harvest plans for healthy stocks or evaluate conservation actions for imperiled stocks.
In the past year we have refined our focus to the following objectives:

1. Develop tools to understand and predict coho salmon marine and freshwater survival variations with environmental variables
2. Use these tools to estimate past and projected (future) statistics of environmentally-forced variations in coho productivity, specifically to:
a. Generate retrospective analyses of environmetally-driven changes in coho survival rates based on climate records dating to the early 20th century
b. One-year lead time coho abundance forecasts
c. Projections for coho productivity in the 21 st century based on regionallydownscaled IPCC climate change scenarios

## Approach

Our analysis requires us to separate the year-to-year variations in marine and freshwater survival rates, in order to explicitly model variations in survival rates as a function of environmental changes. We have chosen to focus our analysis on western Washington coho salmon, and to adopt a similar analysis strategy as employed by Logerwell et al (2003) in their study of Oregon Production Index coho salmon. We chose to focus on Washington coho salmon for the following reasons:

- Long term data is available to estimate marine survival from both wild and hatchery stocks in western Washington. Extensive tagging and trapping of smolts from wild index populations by the Washington Department of Fish and Wildlife (WDFW) provides longterm data which allows us to include several wild coho populations in our analysis.
- A regional focus including multiple populations will allow for an assessment of subregional scale patterns of covariation.
- Synergy with a University of Washington Climate Impacts Group project to develop climate change scenarios for multiple aspects of Washington State climate in the 21st
century will allow us to use their climate change scenarios in our assessment of future trends in coho salmon productivity.

Given these objectives, the project consists of 4 main tasks:
Task 1 (completed, see below): Develop a database for marine survival rates and possible environmental predictive variables from 1970-present

Task 2 (preliminary analysis completed, see below): Objectively identify patterns of covariation among stocks and develop time series for sub-groups

Task 3 (underway): develop models for explaining and predicting coho marine survival variations with environmental and biological data

Task 4 (winter/spring/summer 2009): use historic environmental data to estimate statistics of modeled coho marine survival patterns back to early 20th century; use projected environmental data from IPCC-based climate change scenarios to estimate coho marine survival statistics into the late 21st century

## Work Completed

Jessica Beetz, the Graduate RA being funded by this project, completed her first year of coursework, wrote two drafts of a M.S. thesis proposal, and made substantial progress in carrying out research tasks for this project.

Specifically, she has completed Task 1 by developing a dataset of coho marine survival estimates from the Pacific States Marine Fishery Commission's (PSMFC) Coded Wire Tag (CWT) collection. The database consists of 23 hatchery and 5 wild stocks for streams draining into Puget Sound and the outer coast of Washington (Figure 1). The time series begins in brood 1970 and ends in 2004.


Figure 1: Map showing locations for coho populations with marine survival data used in this study. Red (blue) shading indicates wild (hatchery) populations. Hatchery marine survival rates were obtained from the PSMFC CWT database, while marine survival rates for wild stocks are from WDFW index streams.

Preliminary results from Task 2, objectively identifying patterns in the coho marine survival data, include the following:

- Pairwise correlations between these marine survival time series show a strong tenency for regional coherence, with very low correlations between most Puget Sound and Washington coast populations, and a tendency for positive correlations for stocks within Puget Sound or in coastal populations.
- Little evidence for a distance effect on the strength of pairwise correlations between marine survival time series.
- Different analytic approaches objectively identify 4 different regionally coherent groups of marine survival time series: (1) high and variable survival rates for wild stocks in Puget Sound; (2) a Puget Sound group with sharp declines in marine survival beginning in the late 1980s; (3) a coastal hatchery group with relatively low and highly variable marine survival rates; and (4) a Puget Sound hatchery group with a declining trend in marine survival that reversed in the mid-1990s (Figures 2 and 3)



## Applications

The successful completion of this project will be valued by researchers and resource managers concerned with understanding the variability and predictability of climate sensitive natural resources. For example, the results from this project will be of immediate interest to salmon fishery managers at WDFW, who annually are charged with making run-size forecasts that are used in the annual harvest planning and allocation process. Beetz has met with WDFW coho researchers frequently in the past year, and will continue to communicate with them over the life of this project.

The state of Washington is also currently engaged in planning for the impacts of climate change, and the results of this study will inform those discussions. Mantua and collaborators in the UW Climate Impacts Group are currently drafting a series of reports on the impacts of climate change for Washington's resource managers, and this work will add valuable information for salmon managers. Other research groups are carrying out related studies to better understand the ways in which climate influences marine resources. Scheuerell and Zabel are using multivariate time series models to evaluate patterns in abundance and the degree of synchrony among populations. The various results from all of this work will be presented at two international conferences in 2009: the $11^{\text {th }}$ Annual Pacific Salmon Ocean Ecology Meeting and the Puget Sound-Georgia Basin Ecosystem Conference. We also expect to make additional presentations at other scientific meetings.


## Status

As we did not receive our money until midway through the fiscal year in 2006, we were unable to recruit a graduate student at the University of Washington for the 06-07 academic year. We recruited Jessica Beetz and she began her research in August 2007 at the UW School of Aquatic and Fishery Sciences under the direct supervision of Mantua, and she is on track to complete her M.S. thesis in the summer of 2009. Our grant is set to expire August 30, 2008, but we expect that NOAA will grant our request for an extension through the end of 2008.

## Publications

We are currently working on 3 publications from this research, with working titles of:

1. Patterns of covariation linked to environmental change in western Washington coho marine survival rates.
2. A new tool for hindcasting and forecasting coho marine survival at local to regional scales.
3. Projected impacts of anthropogenic climate change on western Washington coho salmon the $21^{\text {st }}$ century.
We are pleased that Beetz has taken on a leading role in the production of these manuscripts as a direct extension of her thesis.

## Presentations

Mantua N, Mote P, Salathe E, Duliere V, Jump E. Observed and projected climate trends in the Pacific Northwest. Western Division American Fisheries Society Meeting, Portland, OR, May 5-8, 2008.

## Literature cited

Crozier L, Zabel RW. 2006. Climate impacts at multiple scales: evidence for differential population responses in juvenile Chinook salmon. Journal of Animal Ecology 75, 11001109.

Logerwell EA, Mantua NJ, Lawson PW, Francis RC, Agostini VN. 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (Oncorhynchus kisutch) marine survival. Fisheries Oceanography 12, 554-568.
Quinn TJ, and Deriso RB. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.
Scheuerell MD, Williams JG. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer Chinook salmon. Fisheries Oceanography 14, 448-457.
Zabel RW, Scheuerell MD, McClure MM, Williams JG. 2006. The interplay between climate variability and density dependence in the population viability of Chinook salmon. Conservation Biology 20, 190-200.

06-14
Project Title: Fishery indices for the Southeast Atlantic (FISEA): Biological indicators of coastal and estuary dependent fishery production in the U.S. South Atlantic. Year 2

## Principal Investigators:

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## Background and Goals

The Beaufort Inlet Ichthyoplankton Sampling Program at the NOAA Center for Coastal Fisheries and Habitat Research is the longest consecutive ichthyoplankton sampling program along the US east coast, representing a 21-year time series of larval fish ingress through one of five major inlets into North Carolina estuaries. Research efforts using these data have addressed timing of immigration, age and size characteristics of larvae, inferences on spawning sources and biophysical linkages to larval transport. Many of the most abundant species that are sampled are members of a guild that spawn near the continental shelf in the fall and winter, the larvae are transported shoreward and ingress through inlets in the Southeast US into estuarine nursery habitats. We proposed to assess the utility of larval ingress measures as indices of population status for commercially, recreationally and ecologically important finfish species. Our original objectives for the second year of our two-year FISEA initiative were focused on assessing the utility of larval ingress measures as abundance indices for species that spawn in spring/summer, such as Gag grouper.

Gag grouper (Mycteroperca microlepis) are of great importance to both commercial and recreational fishermen in the southeastern states. The recent stock assessment which classified gag as overfished, depended entirely on fishery dependent data (SEDAR, 2008). This assessment was questioned because of the lack of fishery independent data. There is neither an adult or juvenile fishery independent index of abundance in North Carolina. Our project will provide information for developing a fishery independent index of abundance for gag grouper. A larval/juvenile abundance index could also be used as a proxy for the adult population. This will be accomplished by tracking the young-of-the-year cohort through its juvenile phase by capturing gag grouper during ingress (larvae), estuarine residence (juveniles) and emigration (egressing juveniles). More specifically, the goals of this project are the following:

1. To determine the timing of recruitment of gag into Beaufort Inlet, NC and estimate the spawning dates of ingressing gag.
2. To identify important habitat characteristics in areas with high trawl catch-per-uniteffort (CPUE).
3. To determine if a sampling protocol can be developed that will provide estimates of relative abundance of gag with low variance, and that will not be overly labor intensive (e.g. sampling large volumes of water every night for post-larval gag, or sampling a large number of submerged aquatic vegetation (SAV) beds for juvenile gag).
4. To test for changes in cohort structure from ingress to egress and estimate growth rates.

## Approach

## 1. Recruitment of gag into Beaufort Inlet, NC (Bridgenet)

The period of ingress for gag grouper (April-May) was determined by examining historical data from the 21-year time series of larval fish ingress data from the Beaufort Inlet Sampling Program at NOAA (bridgenet), and interpreting our results in relation to those from Keener et al. (1988) in South Carolina. Our data set was generated using a 1 x 2 m neuston net fished once weekly. Ichthyoplankton sampling was conducted from the bridge spanning the channel to Pivers Island, NC, 1 km upstream from Beaufort Inlet.

Due to the rarity of gag grouper in historical ichthyoplankton samples (see historical summary below), sampling in 2007 and 2008 was carried out on a nightly basis from April through early June in an attempt to sample the peak ingress. A $1 \mathrm{~m}^{2}$ ring net was used because of its ease of deployment for nightly work. Four consecutive 10 minute tows were conducted each night. Densities were calculated using the number of gag caught and the volume of water sampled on a per tow basis $\left(\# / \mathrm{m}^{3}\right)$; mean density of gag for a given night will be the average of the four tows. The relative magnitude and timing of ingress into Beaufort Inlet will be determined.

## 2. Developing an efficient sampling protocol with low variance

Larval and juvenile gag are rare. In order to reduce the labor costs associated with indexing juvenile gag grouper, bridgenet and trawl data will be analyzed for possible predictors of gag catch. Densities of gag larvae in the bridgenet will be correlated with lunar cycle and tidal heights. Seagrass species, percent seagrass coverage, water temperature, and proximity to Beaufort Inlet will tested for affect on gag catch. Results from these analyses will allow future sampling efforts to be streamlined so sampling will only occur during times and places when the probability of capturing gag is high.

## 3. Identify characteristics of habitats with high trawl catch-per-unit-effort (CPUE)

Juvenile gag were sampled in seagrass beds during the summer months (June-Sept) using a $6-\mathrm{m}$ otter trawl. A new set of twenty randomly selected points within seagrass beds were sampled every two weeks (Figure 1). Data on water temperature and species of seagrass present (eel grass vs. shoal grass) were recorded at each sites trawled. A subset of sites with gag and a subset
of sites without gag were then randomly selected to assess the percent coverage of seagrass using the Braun-Blanquet criterion $(0=0 \%, 1=1-5 \%, 2=6-25 \%, 3=26-50 \%, 4=51-75 \%, 5=75-$ $100 \%$ ). Due to the shallow nature of seagrass beds ( $1-3 \mathrm{ft}$ ), field work could only be conducted at high tide. Therefore, all trawled sites could not be assessed for grass coverage due to time constraints.


Figure 1: Randomly selected trawl sites. Five sets total ( $\mathrm{n}=100$ for 2007), each represented by a different color. Also shown is location of bridgenet in relation to Beaufort Inlet

## 4. Testing for changes in cohort structure from ingress to egress and estimating growth rates

In addition to the sampling of ingressing larvae and resident juveniles, we have collected egressing juvenile gag. Egressing juveniles are collected using commercial channel nets during October and November. Hatch dates of all three life stages (larval, estuarine juvenile, egressing juvenile) will be back-caIculated using daily growth increment counts from lapilli otoliths. We will determine if there were changes in distributions of hatch dates by life stage; the mean and CV of hatch dates will be compared among these three groups to test for selective loss. This will be important when deciding which gear type is most effective for indexing young-of-the-year gag. It will be important to know that the fish caught in the bridgenet and trawls are surviving to migrate offshore (and assumed to contribute to the adult population). Also, information on hatch dates and age at ingress will be compared to that found by Keener et al. (1988) in South Carolina.

## Work Completed:

## 1. Recruitment of gag into Beaufort Inlet, NC (Bridgenet)

## 2007

Nightly sampling started May 14 and continued through June 20. Historically, CPUE of postlarval gag peaked in late April to mid-May; during nightly sampling, larval gag ingress was zero on most nights with the exception of a 7-day period in mid-May when 88 percent of the five week total was caught (Figure 2). A total of 26 larvae were caught in over 5 weeks of nightly sampling started April 2 and continued nightly through May 29. A total of 16 gag were caught with two small pulses; 5 fish in April, 8 in May.


Figure 2: Post-larval ingress of gag grouper from bridgenet data.
2008

## 2-3. Developing an efficient sampling protocol with low variance <br> Identify important habitat characteristics in areas with high trawl catch-per-unit-effort (CPUE)

Although not significant, probability of catching a gag increased with increasing seagrass coverage. CPUE was greater in high density seagrass (Figure 3). Gag did not show a preference for seagrass species (Figure 4). CPUE peaked in early July, decreasing gradually thereafter; likely due to emigration out of the estuaries (Figure 5). Lower catch in bridgenet samples seems to be tracking to lower trawl CPUE in seagrass beds.


Figure 3: Presence/absence of gag grouper and proportion of gag grouper in relation to percentage seagrass coverage.


Figure 4: Mean catch of gag grouper in Zostera marina (eel grass) and Halodule wrightii (shoal grass) was not significantly different.


Figure 5: CPUE with trawl in seagrass beds peaked in early July 2007
4. Testing for changes in cohort structure from ingress to egress and estimating growth rates

Otolith preparation and analysis is in progress. Growth rate was estimated from the gag caught in 2007 (Figure 6). A sigmoidal growth trajectory was found with a summertime growth rate of 1.6 mm per day. High $\mathrm{R}^{2}$ value and low dispersion suggests a single cohort. Otolith examination will provide more evidence for cohort structure.


Figure 6: Sigmoidal growth trajectory with rapid growth through the summer months

## Applications:

Management has experienced difficulty in supporting decisions to reduce fishing pressure on gag grouper because of the uncertainty in the stock estimates generated using only fishery-dependent data. Currently, model predictions are used to estimate gag recruitment. A juvenile abundance index can be a key component reducing the uncertainty of the stock assessment.
Information on age structure obtained from otoliths is useful because it allows for tracking a cohort through time and determining which sub-cohorts (i.e. weekly cohorts) are contributing most to the population. This will be useful in deciding which gear type would be best for indexing gag that might eventually contribute to the adult stock. Back-calculating fertilization dates to determine when these gag were spawned might provide insights into when spawning is most successful for gag grouper; this can be compared to times of current fishing closures that were based on gonad analysis (SAFMC, Gag grouper report 2006).
We continue to make progress on developing indicators for use in stock assessments from our year-1 objectives. Specifically, indices of larval and juvenile abundance have been developed and are being used in the revision to the southern flounder (Paralichthys lethostigma) stock assessment, currently under review by the NC Division of Marine Fisheries (Moore and Taylor 2008). Other species-specific indices have also been produced for other species and will be made available to state and regional management agencies for use in stock assessments.

## Referenced papers:

Keener, P., G.D. Johnson, B.W. Stender, E.B. Brothers \& H.R. Beatty. (1988). Ingress of postlarval gag, Mycteroperca microlepis (Pisces: Serranidae), through a South Carolina barrier island inlet. Bulletin of Marine Science 42, 376-396.

SAFMC. SEDAR 10 Stock Assessment Report: South Atlantic Gag Grouper. Stock Assessment Report 1, 2006.

## Publications/Presentations/Webpages:

Presentations (bold denotes FATE/FISEA PIs)
K.W. Able, M.C. Sullivan, R.K. Hagan, J.A. Hare, H.J. Walsh, J.C. Taylor. 2006. Patterns of Summer flounder ingress from two, U.S. east coast estuaries. Poster presented in Early Life History of Fishes Symposium at the American Fisheries Society, Lake Placid, NY.

Able, K., G. Bath-Martin, J. Buckel, and S. Hagan 2006. Larval supply to estuarine habitats: plans/progress to develop a Coastal Collaboration on Recruitment (CCOR). Paper presentation in "Estuarine dependent fishes: patterns and processes of environmental influences on nursery habitat quality" symposium at American Fisheries Society, Lake Placid, NY.

Taylor, J.C. 2007. Climate variability and human impacts: the source and fate of juvenile fishes in NC estuaries. UNC-Institute of Marine Sciences, Morehead City, NC 13 April 2007.

Taylor, J.C., J. Buckel, G. Martin, K. Shertzer. 2007. FISEA: Biological indicators of fishery production in coastal and estuary-dependent fisheries in the southeast US Atlantic. Annual FATE Investigators Meeting, San Jose, CA, 27 August 2007.

Mitchell, W. J. Buckel, J.C. Taylor, G.B. Martin, K. Shertzer. Icthyoplankton Ingress Patterns at a North Carolina Inlet: Evidence for Temporal Shifts in Species Assemblage in Long-term Shifts in Faunal Assemblages in Eastern North America .Annual ERF meeting November 2007

Taylor, J.C., J. Buckel, G.B. Martin, K. Shertzer. Fisheries Indicators for the Southeast Atlantic: Ecosystem change and links to climate variation. NOAA in the Carolinas Annual Meeting, Beaufort, NC, 7 February 2008.

Adamski, K.A., J. Buckel, G.B. Martin, J.C. Taylor, W.A. Mitchell, K. Shertzer. Developing an index of abundance for gag grouper in North Carolina: preliminary results. Tidewater AFS meeting. March 2008.

Martin, G.B., J.C. Taylor, W.A. Mitchell, J.A. Buckel, K. Adamski, K.W. Shertzer. Larval ingress observations from a long-term sampling program at Beaufort Inlet, North Carolina, USA: temporal patterns and relevance to coastal fisheries. $32^{\text {nd }}$ Annual Larval Fish Conference, Kiel, Germany, August 2008.

Taylor, J.C., H. Walsh, W. Mitchell, K. Shertzer, G.B. Martin, J.A. Hare, J.A. Buckel. (In Review) Relationships between larval and juvenile abundance of winter-spawned fishes in North Carolina, USA. Submitted to: AFS Marine \& Coastal Fisheries.

Able, K.W., M.C. Sullivan, J.C. Taylor, G.B. Martin, J.A. Hare, R. Hagan. (In prep) Is there a relationship between summer flounder stock size and fishery independent larval monitoring?

Moore, T. and J. C. Taylor. 2008. Juvenile and larval abundance indices working paper, 2008 Stock Assessment: Southern Flounder, North Carolina Division of Marine Fisheries, Morehead City, NC.

## 06-17

Project Title: I. Building a Framework For Fisheries Forecasting: Understanding Nonlinear Couplings between Fishing, Climate Change and Variability in Fish Populations. II. A Retrospective Analysis of Nonlinear Forecast Methods for Fisheries Ecosystems.

Principal Investigators and Students: George Sugihara, Roger Hewitt, Chih-Hao Hsieh, Christian Anderson

## Goals:

1) Understanding the sources of variability in marine fish populations (separating anthropogenic effects from natural causes).
2) Investigate the applicability of modern time series forecasting methods, and develop new methods for extracting information from time series data.
3) Establish baseline information for predictive models of the CCE. And other fisheries of opportunity (for which appropriate data are available).

## Approach:

1) The project objective of understanding sources of variability (both anthropogenic and environmental) is addressed by using historical icthyoplankton data for the southern CALCOFI domain. These unique data were used to answer a classic question in marine fishery management: whether fishing itself will increase or dampen the population variability of targeted fish species.
2) The project objective using nonlinear methods to improve stock prediction directly addresses the overall NOAA Fisheries mission. It is essential information for setting harvest targets of fished species in the CALCOFI domain.
3) Demonstrating the applicability of the forecasting technology and refining the methods to apply specifically to data of this kind produces base-line information required to build predictive models for the CCE. How much predictability is there and how complicated do the models need to be? Additionally, the nonlinear methods developed here can identify what the coupled ecological subsystems (e.g, communities) are, for the larger national mission of ecosystem-based management.

## Work Completed:

We have obtained the following results:

1) Found fishing increases boom and bust variability of exploited populations. This is a classical question in fisheries science that we were able to answer generally and empirically for the first time. (Mentioned by VAdm Lautenbacher at the National Academies of Sciences November 2006). The implication of this work is that the destabilization of the population is a consequence of common fisheries practices that target the larger older individuals. Thus it is significant to restore age-structure in rebuilding depleted stocks.
2) Confirmed that fishing results in a truncated age and size structure for the population, and further related this to destabilization of exploited populations.
3) Found nonlinear forecast methods are effective for fisheries. These methods work best when the time series composite is constrained by habitat type or region.
4) Found physical data for CCE are best described as linear stochastic (auto-correlated noise). They are high dimensional and effectively stochastic.
5) Found low dimensional nonlinearity in the population dynamics of both exploited and unexploited populations. Dimensionality is a fundamental constraint on the complexity of a model required to achieve a given level of predictability.

## Applications:

Our results to date suggest that:

1) Time series forecasting methods should be deployed at very least as a supplement to existing stock assessment practices. They are shown to have significant forecast skill.
2) Fishery management policy and practices/technologies need to be developed to preserve age-size-structure of exploited populations. "Stop picking on the big guys" as the tabloids say.

## Journal Articles: (all articles are in reviewed journals)

1) Anderson, C., C. Hsieh, S. Sandin, R.Hewitt, A. Hollowed, J. Beddington, R.M. May (2008) Why fishing increases variability of exploited stocks. NATURE (2008), April 17 issue.
2) Hseih, CH., C.S. Reiss, R.P. Hewitt and G. Sugihara (2008) Spatial analysis show fishing enhances the climatic sensitivity of marine fishes. Canadian Journal of Fisheries. April 17, 2008 issue.
3) May, R.M., S.A. Levin, and G. Sugihara (2008) Ecology for bankers. NATURE (2008) March issue.
4) Maye, A., CH. Hsieh, G. Sugihara, B. Brembs (2007). Order in spontaneous behavior in Drosophila. PLOS.
5) Hseih, CH., C. Anderson, G. Sugihara (2007), Extending nonlinear analysis to short ecological time series. American Naturist. (December 2007 issue).
6) Hsieh CH, Reiss, C.S., Hunter, J.R., Beddington, J.R., May R.M., Sugihara G (2006) Fishing elevates variability in the abundance of exploited species. NATURE, 443, 859-862.
7) Southwood, T.R.E, R.M. May, G. Sugihara (2006) Some observations on related ecological exponents. PNAS USA: 2006;103;6931-6933.
8) Hsieh CH, Glaser SM, Lucas AJ, Sugihara G (2005) Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. NATURE 435: 336-340.
9) Hsieh CH, C. Reiss, W. Watson, MJ. Allen, JR. Hunter, RN. Lea, RH. Rosenblatt, PE Smith, G. Sugihara (2005) A comparison of long-term trends and variability in populations of larvae of exploited and unexploited fishes in the Southern California region: A community approach.
Prog. Oceanography 67:160-185.

## Books/Articles-in-Books:

1) May, R.M, Crawley, Sugihara, 2007, Multispecies Patterns, in Theoretical Ecology
2) Sala, E. and G. Sugihara 2004. Food-web theory provides guidelines for marine conservation. In Aquatic Food Webs, ed. J. Cohen, pgs 170-183.

Reports:

1) New Directions in Systemic Risk in The Financial Sector, (NAS Report in Press)
(Reviewed and produced by National Academy of Sciences Board on Mathematical Sciences and it's Applications, and the Federal Reserve Bank)
2) SAP4.2 Writing team on "Critical Ecological Transitions and Environmental Change" (in progress).

## Conference Proceedings/Workshops:

1) Theoretical Ecology (Conference to honor Lord May, Oxford 2006)
2) $\mathbf{2 0}$ Years of Nonlinear Science in the Geosciences, (Workshop, Rhodes 2006).
3) Early Warning Signals of Critical Transitions (Workshop with Marten Scheffer et. al. 2007).

Distinguished Lecturer, Rutgers Institute of Marine Science (May 2008)
Ph.D. Dissertations:
Chih-Hao Hseih 2006.

07-01
Project Title: Developing zooplankton and larval indices for use in Atlantic herring (Clupea harengus) stock assessments

## Principal Investigators:

Jonathan Hare ${ }^{1}$, William Overholtz ${ }^{2}$, Kenneth Able ${ }^{3}$, and David Richardson ${ }^{4}$
1 - NEFSC, Ecosystem Processes Division, Oceanography Branch
2 - NEFSC, Resource Evaluation and Assessment Division, Population Dynamics Branch
3 - Rutgers University, Institute of Marine and Coastal Sciences, Rutgers University Marine Field Station
4 - joined project as NRC Post-doctoral Research Associate

## Goals:

The three primary goals of the project were:

1) To develop an index of larval abundance that could be used to calibrate the herring stock assessment
2) To quantify changes in the spatial patterns of herring spawning over time.
3) To determine the environmental factors (e.g., zooplankton, salinity, temperature) associated with year to year variability in herring recruitment, and multi-year fluctuations in herring populations

## Approach:

Goal 1 - One of the major challenges in analyzing the available ichthyoplankton data results from inconsistency in the seasonal allocation of sampling over the past 37 years. This inconsistency precludes the use of many previously established analytical approaches for developing a larval index. For that reason, a novel non-linear least-squares approach was developed for the calculation of the abundance index. This approach uses information on the age structure and abundance of the sampled larvae on each survey cruise to derive the annual indices of abundance, as well as parameters describing larval mortality and the seasonal cycle of spawning. The appeal of using this approach is that an index can be calculated even in years when the sampling missed a majority of the spawning season.

Goal 2 -To address temporal changes in the distribution of herring spawning, a method is currently being developed that uses non-parametric statistics. This approach involves gridding the study area, and then dividing the time series into $\approx 5$ year periods of data. Once this is done, it is possible to test, within each grid cell, whether a significant increases or decreases in larval abundance has occurred between two time periods. As with the previously described analytical technique, this approach is suitable for dealing with inconsistencies in the timing and spatial allocation of sampling. Furthermore the results of the approach are easy to visualize, and provide more spatial information than the standard geographic center of mass calculation.

Goal 3-To determine the relationships between environmental variables and Atlantic herring stock dynamics, a number of analyses are planned. First, we will investigate the relationship between zooplankton indices (developed from either the Continuous Plankton Recorder data or from the shelf-wide bongo net sampling programs) and SSB and recruitment. Based on the
extent to which we observe a relationship between these factors, we will explore the effects of variability in oceanographic conditions that have been shown to impact regional productivity (e.g. large-scale circulation changes), or may be hypothesized to affect the survival of herring eggs (e.g. bottom temperature) and larvae.

## Work Completed:

Work officially started on the project in January 2008 when David Richardson started on an NRC post-doc. His funding extends until January 2010. Reports on this project will be made in 2008 (this report), 2009, and 2010.

Goal 1 - The least-squares routine used to derive a larval index of abundance has been developed and applied to the larval herring data. Efforts are currently underway to develop confidence intervals for this approach. Over the 36 years of this time series, a strong correlation is evident between the larval index and the recent stock assessment estimate of biomass. This work is currently being prepared for submission to the Canadian Journal of Fisheries and Aquatic Sciences or a comparable journal. The Matlab scripts used for this approach are also being refined to ensure that new data can readily be added as it becomes available, and that the methodology can be applied to other species with minimal modification to the scripts.

Goal 2 - The analysis of changes in the spatial distribution are preliminary, but suggest notable shifts in the distribution of spawning over the past decades. The previously documented loss of spawning on Georges Bank in the late 1970's and early 1980's is evident in this approach, as is an eastward shift in spawning on Georges Bank from 1990-2004.

Goal 3 - The analysis of environmental factors associated with year to year variability in herring recruitment remains to be done.

## Applications:

We are committed to working with the stock assessment process to include relevant results from this study. The larval index developed as a part of this project will be directly incorporated into the 2009 stock assessment of Atlantic herring. It is hoped that information on the changes in the distribution of spawning also will help guide the allocation of fishing effort. Additionally, due to the key ecological role of herring, the analyses conducted during this project should aid in a broader interpretation of long-term changes in the Gulf of Maine/Georges Bank ecosystem and should contribute to the development of an Integrated Ecosystem Assessment.

## Publications/Presentations/Webpages:

Richardson, D.E., Hare, J.A., Overholtz, W.J. (to be presented Aug 2008) Development of longterm larval indices for Atlantic herring (Clupea harengus) in the northwestern Atlantic Ocean. FATE Annual PI Meeting 2008 - La Jolla, California

Richardson, D.E., Hare, J.A., Overholtz, W.J. (to be presented Sept 2008) Development of longterm larval indices for Atlantic herring (Clupea harengus) in the northwestern Atlantic Ocean. ICES Annual Science Conference 2008 - Halifax-Canada

Project Title: Evaluating Temperature Induced Shifts in Stock Location
Principal Investigators: Jason Link, Michael Fogarty, Jon Hare, Larry Jacobson, William Overholtz

## Goals:

We proposed to examine a set of survey abundances to calculate a weighted "center of gravity" for a suite of common northwest Atlantic fish stocks both annually and in five-year time periods for the past 40 years. We also examined changes in depth distribution, temperature of distribution, and area of occupancy. We then used multivariate techniques to compare changes in distribution with known increases in temperature and changes in stock abundance to establish, if any, relationships between temperature, fishing and stock distribution. Finally, we will then amplify this to a more generic framework of selection criteria employable in any stock assessment context.

## Approach:

Several metrics were used to detect and summarize changes in spatial distribution of 36 fish stocks using the NEFSC spring trawl survey that has occurred on the Northwest Atlantic continental shelf since 1968. The data collection and sample processing methods are described in Azarovitz (1981). We chose 36 stocks to investigate because these species were caught in every year of the spring survey and they were consistently caught in relatively high numbers. Those species that are currently assessed as separate stocks were analyzed separately in this analysis as well.

The 5-year biomass-weighted centers of abundance for each of 9 time periods were shown for each stock. However, for statistical analysis, mean latitude, longitude, temperature and depth of occurrence were calculated for each year for each stock with the general formula:

$$
X_{j}=\frac{\sum_{i=1}^{n} w_{i} X_{i j}}{\sum w_{i}}
$$

where $X$ is the parameter of interest (latitude, longitude, temperature or depth), $j$ is the survey year, $w_{i}$ is the biomass ( kg ) for each station $i$. Only strata that were consistently sampled over the spring survey time series were used because in some years additional strata were added to increase spatial coverage. Specifically, strata south of Cape Hatteras and in the Western Scotian Shelf were omitted. To calculate mean annual relative abundance, biomass tow ${ }^{-1}$ was summed for each strata and then biomass was weighted by the number of tows within a stratum and stratum area.

To statistically test for changes in spatial distribution measures over time we conducted linear regressions incorporating the appropriate autocorrelation structure for each stock. We did a separate linear regression for each stock and for each distributional measure (mean distance, mean depth, mean temperature, area occupied, and maximum latitude). ArcGIS software was used to create smoothed maps in five-year time blocks of several representative species using the inverse distance weighting (IDW) method. The spatial pattern of mean annual bottom
temperature for each 5 year time block was depicted using IDW in ArcGIS, in the same manner that species distributions were smoothed.

Because there are many possible distributional responses of fishes to changes in both temperature regime and population abundance, we used canonical correlation analysis (CanCorr) to examine the linear relationship between multiple response variables and multiple explanatory variables in each species. The response variables included mean distance, mean depth, mean temperature, minimum latitude, maximum latitude, and area occupied. The explanatory variables included SST, AMO, NAO, BT, FEB and relative biomass (BIOMASS).

## Work Completed:

We detected clear changes in spatial distribution of majority of the 36 fish stocks that we examined in the Northwest Atlantic, and statistically significant changes that are consistent with recent warming in 16 of these stocks. Distributional changes were evident for species across many families, life histories, and habitat preference. Responses were most pronounced in stocks whose center of abundance was historically in SNE and MAB. The center of abundance for most of the southern stocks moved to the northwest over the time series. Northern stocks, particularly those traditionally found in the GOM, including the northern red hake stock moved poleward only slightly. Thus, the bathymetry and geography of the survey area was important in detecting changes in spatial distribution. Stocks that were restricted to the GOM did not exhibit northward shifts in center of abundance, but many exhibited increases in mean depth and temperature of occurrence.

CanCorr effectively separated out the effects of warming from fishing pressure for most of the stocks we examined. The overwhelming response of these stocks to warming was a poleward shift in centroid of abundance and the response to increases in biomass was a range expansion. CanCorr analysis also emphasized that distributional responses involve the complex interaction between abundance and environmental forcing. Consistent with hypothesized spatial shifts induced by warming, southern species at the northern extent of their range shifted their center of abundance north, but also experienced more favorable conditions for growth and recruitment resulting in abundance increases and range expansion. Northern species at the southern extent of their range, shifted their center of abundance north, but experienced range contraction, were found at increasingly greater depths, and many experienced decreases in abundance.

## Applications:

As part of our ongoing efforts to add ecosystem terms of reference (ECO TOR) to stock assessments, we are moving from solely ecological ECO TOR towards both environmental and ecological ECO TOR. The analyses conducted to date have provided context and background information for many of the assessed species, particularly those in the recent GARM III. The final phase of this project (to be completed in Q1 of FY09 due to the later start time of the FATE post-doc) will be to synthesize the proposed generic framework of selection criteria for stock assessments. That is, based upon this meta-analysis we will develop a generic "checklist" of when and under what conditions various environmental effects should be considered in stock assessment models.

## Publications/Presentations/Webpages:

## Publications:

J.A. Nye and J.S. Link 2008. Changes in the distribution of Northwest Atlantic fish stocks in response to climate change and fishing pressure. ICES Annual Science Conference. Halifax, Canada. ICES CM 2008/E: 1036 pp.
J.A. Nye, A. Bundy, N. Shackell, K.D. Friedland, and J.S. Link. Poissons sans frontiers: Comparing contiguous surveys for major ecological and commercial species in the Northwest Atlantic, with a focus on trends, synchronies and coherences. ICES CM 2008/E:16 47pp.
J.A. Nye and J.S. Link 2008. Meta-analysis of changes in spatial distribution of Northwest Atlantic fish stocks: the relative effects of temperature and abundance. (In NEFSC Internal Review; To be submitted Marine Ecological Progress Series, September 2008)
J.A. Nye, A. Bundy, N. Shackell, K.D. Friedland, and J.S. Link. Poissons sans frontiers: Comparing contiguous surveys for major ecological and commercial species in the Northwest Atlantic, with a focus on trends, synchronies and coherences. (In NEFSC Internal Review; To be submitted ICES J. Mar. Sci, September 2008)

## Presentations:

Nye, J.A., J.S. Link, M. Fogarty, J. Hare, W. Overholtz, and L. Jacobson. Overview of temperature-induced shifts in stock location in the Northwest Atlantic ecosystem. FATE Annual meeting, La Jolla, CA

Nye, J.A. and J.S. Link 2008. Changes in the distribution of Northwest Atlantic fish stocks in response to climate change and fishing pressure. ICES Annual Science Conference. Halifax, Canada.

Bundy, A., Shackell, N., Nye, J., Friedland, K. and Link, J. 2008. Poissons sans frontiers: Comparing contiguous surveys for major ecological and commercial species in the Northwest Atlantic, with a focus on trends, synchronies and coherences. ICES Annual Science Conference. Halifax, Canada

07-03
Project Title: Decadal and basin scale oceanographic variability and pelagic fishery production in the Gulf of Mexico - a synthesis of 30-years of data for management applications

Principal Investigators: William Richards, Barbara Muhling, Andrew Bakun

## Goals:

Overarching goals and objectives of the project.
The overall goal of this project is to incorporate environmental variability into existing larval fish indices, especially those for Atlantic bluefin tuna. Larval fish indices are currently used to refine stock assessment models, and are often the only fishery-independent indices available. Initially, bluefin tuna will be focused on, with habitat preferences of bluefin larvae within the Gulf of Mexico defined using archived data. Temperature preferences will be defined first, using existing CTD data, and then other physical and biological variables will be tested in a similar manner. A simple spatial model will then be constructed to quantify the relationships between environmental variables, and occurrence of bluefin larvae. Variability in the spatial and temporal extent of favourable conditions each year will be used to improve the existing larval bluefin tuna abundance index, and thus stock assessments. Once this is completed, the method can be extended to other species, both exploited and unexploited. In addition, we also aim to use larval fish assemblage data to quantify the influence of decadal-scale oceanographic processes on suites of larval fish assemblages and on the Gulf of Mexico ecosystem as a whole.

The initial objectives of the project ( as per the proposal) were as follows:

1. Analyze initial trends in abundance and distribution of scombrid larvae, and correlations between abundances of exploited and unexploited species.
2. Develop multi-species ecological indicators in the northern Gulf of Mexico.
3. Develop indices of Loop Current variation.
4. Incorporate data on environmental and climatic variability and existing larval fish indices and stock assessment tools to develop recruitment predictors for commercially important species.
5. Collaborate with the PEW Institute for Ocean Science, University of Miami, other NOAASoutheast Fisheries Science Center projects, and NOAA-Atlantic Oceanographic and Meteorological Lab to facilitate regional comparisons within the Gulf of Mexico.
6. Compare similar data collected in the Mediterranean by Instituto Español de Oceanografia (IEO)-Centre Oceanogràfic de Balears, Spain.

## Approach:

Description of the work that was performed.
During the first year of the project, a habitat model has been developed to define where and when bluefin tuna larvae have been found in the Gulf of Mexico in the 30 years since sampling commenced. The model initially used archived data from CTD casts, and was then expanded to include variables extracted from satellite data layers in ArcGIS. In the next few months, this model will be developed further, so that an spatial index defining the probability of occurrence of bluefin larvae can be derived.

Variability in larval fish assemblages has been defined for all stations sampled across the Gulf of Mexico since the early 1980s, using multivariate statistical software such as Primer-6, and

Canonical Analysis of Principal Co-ordinates (CAP). Statistically distinct assemblages have been defined, and these have largely been separated by their location in the Gulf of Mexico. Family groups which were responsible for distinctions between assemblages have been defined. Patterns in assemblage structure suggest some directional changes through time, and we aim to better define these through multivariate methods in the next year of the project. Any significant changes will be related to changes in environmental conditions in the Gulf of Mexico, including those linked to climatic oscillations and ocean-scale processes.

## Work Completed:

Summary of progress, including results obtained / products developed, and their relationship to the goals of the project. If problems developed which resulted in unexpected results, they should be discussed.

Results are discussed in terms of the original objectives of the project. These were:

1. Analyze initial trends in abundance and distribution of scombrid larvae, and correlations between abundances of exploited and unexploited species.
Abundances of scombrid larvae were highly variable temporally and spatially across the sampling period. Larvae of Thunnus spp, Katsuwonus spp. and Auxis spp were abundant throughout the Gulf of Mexico, while Acanthocybium, Euthunnus and Scomberomorus were rarer. While larvae of Thunnus spp. (excluding bluefin tuna) were widely distributed, the occurrence of bluefin tuna larvae appeared to be more driven by environmental conditions. A simple model of bluefin tuna habitat preferences was therefore constructed. The aim of this model was to elucidate the sources of some of the variability in bluefin tuna distribution and abundance, which is highly relevant to the existing larval index.

Relationships between larval bluefin tuna and environmental variables were examined using a preference index, which considers the percentage of stations within each "habitat type" that contain bluefin larvae. Habitat types were defined by $0.5^{\circ} \mathrm{C}$ ranges in sea surface temperature and temperature at 200 m , and by 5 cm ranges for sea surface height anomaly. An example for sea surface temperature only is shown in Figure 1. The same process has been completed for temperature at 200 m , and sea surface height anomaly. In the coming months, these indices will be combined into one multivariate index, which will provide a simple predictor of the probability of bluefin larvae occurring at a station with particular environmental conditions. Generalized Additive Modeling will also be utilized to improve the spatial model, and other environmental predictors such as surface chlorophyll and surface salinity will be examined.

Environmental preferences of bluefin tuna larvae, larvae of other Thunnus species, and larvae of an abundant, unexploited small pelagic genera (Cubiceps) were also examined (Figure 2). Other Thunnus spp. preferred warmer water than bluefin tuna, while Cubiceps spp. had a similar preference. However, unlike bluefin larvae, Thunnus spp. and Cubiceps spp. did not appear to avoid the Loop Current (where the temperature at 200 m was greater than $20^{\circ} \mathrm{C}$ ). The possibility that bluefin larvae tend to be separated temporally and/or spatially from larvae of other tunas, and other species will be further investigated in the coming year. Finer-scale sampling completed in the Gulf of Mexico in 2008 through another funded program will provide us with the data to look at these mechanisms in more detail.


Figure 1: Modeling the response of bluefin tuna larvae to sea surface temperature. a) Frequency distributions for all stations sampled 1982-2004, and for all stations in this time period where bluefin larvae were found, b) Chesson's preference index for each $0.5^{\circ} \mathrm{C}$ sea surface temperature range, c) spatial representation of preference index for a selected year (1983), overlaid with occurrence of bluefin larvae. Crosses show stations where no bluefin larvae were found.


Figure 2: Preferences of bluefin tuna, other Thunnus spp and Cubiceps spp. for sea surface temperature and temperature at 200 m depth conditions over all stations sampled between 1982 and 2004.

## 2. Develop multi-species ecological indicators in the northern Gulf of Mexico.

Similarity profile analysis in Primer-6 software split all stations sampled between 1982 and 2004 into six large assemblage groups (Figure 3). These groups were largely defined by their position in the Gulf of Mexico. Differences in abundances of unexploited mesopelagic taxa were responsible for distinguishing between each assemblage group, with Bregmacerotidae larvae more associated with colder water, and Gobiidae and Scaridae larvae more abundant in warmer waters. Future work will focus on defining the temporal changes in assemblages structure, and relating changes in larval assemblages to variability in environmental and oceanographic conditions.


Figure 3: Multidimensional Scaling ordination of all stations sampled from 1982 to 2004. Similarity profile analysis defined six distinct assemblage groups (top). Abundances of the six families which best distinguished the assemblage groups (from similarity percentage analysis) are shown as bubbles, overlaid on the same MDS ordination (bottom).

## 3. Develop indices of Loop Current variation.

Archived satellite images from the Gulf of Mexico are currently being processed to provide an index of the penetration and strength of the Loop Current from year to year. Once this is completed, the Loop Current index will make a valuable addition to our existing models predicting both the probability of finding bluefin tuna larvae, and of the larval fish assemblage structure across the Gulf of Mexico. As bluefin larvae in particular have been shown to avoid the Loop Current, the effect of strong vs. weak flow of the Loop Current on distribution and abundance of bluefin larvae will be investigated.
4. Incorporate data on environmental and climatic variability and existing larval fish indices and stock assessment tools to develop recruitment predictors for commercially important species.
The habitat models that we are developing, for bluefin tuna larvae in particular, are focusing on developing a simple, robust output which can be incorporated into the current larval index. If the current larval index can be adjusted in terms of the environmental conditions at the time of sampling, then inputs to the stock assessment models will be more accurate. Discussion with stock assessment scientists within NOAA will continue, in order to formulate a product which is most useful.
5. Collaborate with the PEW Institute for Ocean Science, University of Miami, other NOAASoutheast Fisheries Science Center projects, and NOAA-Atlantic Oceanographic and Meteorological Lab to facilitate regional comparisons within the Gulf of Mexico.
Collaborations have been established with the NOAA-Atlantic Oceanographic and Meteorological Lab and University of Miami in particular, mostly with reference to obtaining oceanographic and physical datasets, and for help and discussion on statistical methods. In the next year, we hope to further collaborate with other scientists within the Southeast Fisheries Science Center to discuss the use of other historical datasets collected in the Gulf of Mexico. Through these partnerships, we aim to move towards a more complete understanding of ecosystem processes and decadal-scale trends within the region.
6. Compare similar data collected in the Mediterranean by Instituto Español de Oceanografia (IEO)-Centre Oceanogràfic de Balears, Spain.
A meeting is being planned in early 2009 with scientists from Spain who are currently engaged in similar work on bluefin tuna in the Mediterranean Sea. This will allow us to compare results and discuss potential mechanisms affecting bluefin tuna larvae between the Mediterranean and the Gulf of Mexico.

## Applications:

Describe how results are being used in stock assessments or otherwise benefiting living marine resource management.
Results and hypotheses from our work are being communicated to stock assessment scientists as we continue to work through the data, and develop simple models. Once the habitat models for bluefin tuna in particular are completed, we will meet with scientists involved into the stock assessment for this species, and discuss how our work is most likely to be used in assessments, and the most useful way to incorporate it into current stock assessment models.

## Publications/Presentations/Webpages:

Muhling, BA, Lamkin, JT, Richards, WJ, Bakun, A (2007) "Bluefin Tuna larvae in the Gulf of Mexico: Analysis of twenty nine years of ichthyoplankton collections (19772005)", 1st international CLIOTOP conference - Climate Impacts on Oceanic Top Predators, La Paz, Mexico, 3-7 December 2007.
Muhling, BA, Lamkin, JT, Richards, WJ (2008) Temporal and spatial patterns of larval Atlantic Bluefin Tuna in the Gulf of Mexico: Synthesis of thirty years of data, 32 ${ }^{\text {nd }}$ Annual Larval Fish Conference, Kiel, Germany, 4-7 August 2008.
Muhling, BA, Lamkin, JT, Richards, WJ, Bakun, A (2008) Decadal and basin scale oceanographic variability and bluefin tuna fishery production in the Gulf of Mexico, Fisheries and the Environment (FATE) annual meeting, La Jolla, California, 13-14 August 2008.

Project Title: Index development and ecosystem monitoring and assessment
Principal Investigators: Jennifer Boldt ${ }^{1}$ Anne Hollowed ${ }^{2}$, Kerim Aydin ${ }^{2}$, and Pat Livingston ${ }^{2}$
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## Goals:

Overarching goals:
NOAA requires the implementation of an ecosystem approach to fisheries management that takes major ecosystem components and services into account in managing fisheries. NOAA's goal is to sustain biological communities and marine ecosystems at high levels of productivity and biological diversity so as not to jeopardize a wide range of goods and services from marine ecosystems while providing food, revenues and recreation for humans (NRC 1998). Recently an external ecosystem task team review provided recommendations on implementing an ecosystem approach to management. Their recommendations included the development of regionally-based Integrated Ecosystem Assessments (IEAs) for each large marine ecosystem, conveying information on the status of ecosystem health and evaluating the impacts of current and proposed human activities.

The goals of this project are to develop and evaluate recruitment predictions based on ecosystem indices and to acquire, maintain, and synthesize ecosystem indicators in the Ecosystem Considerations and Assessment, a part of the North Pacific Fishery Management Council's (NPFMC) annual Stock Assessment and Fishery Evaluation document (SAFE). Other goals include augmenting existing research efforts on-going at all six Science Centers, assisting in the production of FATE workshop reports, and working with AFSC and Pacific Marine Environmental Laboratory (PMEL) staff to evaluate the utility of using selected indices in the formulation of stock assessment advice.

Objectives:

- Acquire and maintain ecosystem indicators from about 100 collaborators in the Ecosystem Considerations Section of the SAFE.
- Integrate information regarding ecosystem status and trends and use models to predict possible future ecosystem states using an indicator approach to assemble the eastern Bering Sea (BS)/Aleutian Islands (AI) and Gulf of Alaska (GOA) ecosystem assessments.
- Develop ecosystem indices that will be available for incorporation into Stock Assessment Fishery Evaluation reports and will advance our understanding of marine ecosystem dynamics.
- Provide an index of groundfish stock survival (recruits per spawning biomass anomalies) to detect decadal- or regime-scale changes in stock productivity.
- Develop, validate, and maintain an index of water column structure/frontal regions in the eastern Bering Sea.
- Develop, validate, and maintain indices of size diversity in the BS, AI, and GOA.
- Transfer information from PMEL and AFSC to other research institutions and facilitate regional comparisons.


## Approach:

This approach primarily addresses the second type of proposal in the FATE 2007 request for proposals: synthesis of existing data sets that result in development and validation of ecological indicators which contribute to an integrated ecosystem assessment in all or part of a Large Marine Ecosystem. In addition, this approach has links to the first type of requested proposals: collaborations between ecologists or oceanographers and scientists actively engaged in agency stock assessments with a goal of improving stock assessments through use of FATE indices.

Our approach is to integrate ecosystem indicators into a succinct suite of summary statements regarding the past, present and future state of three major ecosystems: the Aleutian Islands, eastern Bering Sea and Gulf of Alaska (http://access.afsc.noaa.gov/reem/ecoweb/index.cfm). Multivariate and univariate statistical techniques are used to extract general trends in the production and distribution of living marine resources, as well as patterns and trends in core oceanographic indices. These are synthesized to provide an overview of the ecosystem status. These summaries form the foundation of the NPFMC's annual review of ecosystem considerations of the implications of proposed Total Allowable Catch (TAC) specifications. Likewise they form the basis for integrated ecosystem assessments, a fundamental element of Fisheries Ecosystem Plans.

## Work Completed:

1. Acquire and maintain ecosystem indicators from collaborators into the Ecosystem Considerations Section of the SAFE. These indicators are updated annually and the Ecosystem Considerations section of the SAFE is made available to stock assessment scientists, plan team members, the Scientific and Statistical Committee (SSC), Advisory Panel (AP), and NPFMC in the fall of each year. The Ecosystem Considerations section is utilized to advance the understanding of marine ecosystem dynamics and deliver ecological, oceanographic, and climatic indices to stock assessment scientists and managers. The Ecosystem Considerations section includes an ecosystem assessment, updated status and trend indices, and ecosystem-based management indices and information. Integration of information regarding ecosystem status and trends and the use of models to predict possible future ecosystem states using an indicator approach constitutes the framework of a BSAI and GOA ecosystem assessment. Annual updates of historical trend and present status of over 80 indicators are performed. The indicators range from climate, oceanographic, production, species, community, to ecosystem-level indicators as well as ecosystem-based management indicators.

The Ecosystem Considerations report was updated twice in 2007 and a presentation was prepared for the North Pacific Fisheries Management Plan Teams. In September 2007, 21 contributions, the Ecosystem Assessment, and the Executive Summary were updated, and there were 6 new contributions added (some of which addressed recommendations made by the Aleutian Islands Fishery Ecosystem Plan team). The Executive Summary was organized differently to address fishing effects on ecosystems, climate effects on ecosystems, and ecosystem trends. In October and November 2007, 28 contributions were updated and 3 new contributions were added. The Ecosystem Considerations website was also updated:
http://access.afsc.noaa.gov/reem/ecoweb/index.cfm. The Ecosystem Considerations internet website enables viewers to download the report in its entirety, browse individual contributions, and access time series data presented in the report. This allows stock assessment scientists, managers, authors of the EA or EIS, and the public quick and easy access to data and ecosystem information. This also encourages the transfer of information from PMEL and AFSC to other research institutions facilitating regional comparisons.
2. Develop and maintain the Ecosystem Assessment section of the Ecosystem Considerations report: The primary intent of this assessment is to summarize and synthesize historical climate and fishing effects on the shelf and slope regions of the eastern Bering Sea/Aleutian Islands and Gulf of Alaska from an ecosystem perspective and to provide an assessment of the possible future effects of climate and fishing on ecosystem structure and function. The Ecosystem Considerations section of the Groundfish SAFE provides the historical perspective of status and trends of ecosystem components and ecosystem-level attributes using an indicator approach. For the purposes of management, this information must be synthesized to provide a coherent view of ecosystems effects in order to clearly recommend precautionary thresholds, if any, required to protect ecosystem integrity. To this end, the assessment summarizes recent trends by distinct ecosystem properties that require consideration.

This year we continued work on the Ecosystem Assessment to address three of the recommendations that came out of the PICES/NPRB workshop (Seattle, WA June 1-3, 2006): Publish concise, attractive executive summaries, research how to synthesize data into fewer indicators, and develop and utilize formal process of evaluating and selecting indicators. Procedures for rating and vetting indices as well as blending data analysis and modeling into fewer indicators are being examined. We will derive a 'short' list of key indicators to track in the EBS, AI, and GOA, using a stepwise framework, the DPSIR (Drivers, Pressure, Status, Indicators, Response) approach (Elliot 2002). One goal is to have a limited number of indicators that clearly communicate the status of the ecosystem, and indicate the future direction of the ecosystem. The audience for this would be the NPFMC and public.

Also, we have collaborated with Dr. Chang Ik Zhang (Pukyong National University, Korea) and others to utilize a new approach, developed by Zhang et al. (in press), to conduct an ecosystembased risk assessment for the Eastern Bering Sea bottom trawl fishery. Indicators were selected for three management objectives: sustainability, biodiversity, and habitat quality. Target and limit reference points will be chosen for each index and risk scores will be calculated to assess the status of species and the fishery. Nested risk indices will also be calculated to assess the ecosystem status
3. Develop and maintain an index of stock survival (recruits per spawning biomass anomalies) to detect decadal- or regime-scale changes in stock productivity. These analyses are updated annually and have been presented to NPFMC plan team members and utilized in reports and presentations of climate effects on fisheries. Current analyses include utilizing the newly developed sequential $t$-test analysis of regime shifts (STARS; Rodionov 2005, Rodionov and Overland 2005) to detect regime shifts in indices of groundfish recruitment and survival. These analyses were incorporated into a paper entitled: "Patterns of covariation in productivity among Northeast Pacific fish stocks" (Mueter et al. 2007). In that paper, Mueter et al. (2007) found:
"Recruitment and stock-recruit residuals in individual stocks did not show a consistent response to known climatic regime shifts. However, combined indices of pelagic productivity (mostly salmon) and demersal productivity increased in response to the well-documented 1976-1977 climate regime shift, whereas the 1988-89 climate regime shift produced inconsistent or shortlived responses."
4. Develop and maintain an index of water column structure/frontal regions in the eastern Bering Sea. Retrospective analyses suggest that an index of frontal regions and advection in the eastern Bering Sea hold promise for explaining temporal patterns in recruitment of walleye pollock, and winter spawning flatfish (Wespestad et al. 2000, Wilderbuer et al. 2002). Also, water column structure may be related to pollock cannibalism, which would affect recruitment. Several indices of water column temperature and structure/stability have been estimated. A manuscript was prepared describing summer water column structure over the continental shelf in the eastern Bering Sea, 1982-2006 (Buckley et al., in internal review). Problems with the diet database were uncovered and corrected. Data processing and analyses are now underway to examine relationships with pollock cannibalism, while considering predator and prey size. If relationships are found, they can be directly incorporated into the Bering Sea pollock assessment, through direct effects on mortality estimates. Results will be summarized and submitted for publication, providing information useful for evaluating the interaction between this important fish stock and the environment.
5. Develop, validate, and maintain indices of size diversity in the BS, AI, and GOA. Recent efforts to summarize quantitative ecosystem indicators for fisheries management have identified size-based indicators as an important class of indicators for tracking fishery exploitation effects on fish communities (Cury and Christensen 2005, Kruse et al. 2006, Hall et al. 2006). One sizebased indicator that measures fishing induced changes at a system-wide level is the community size spectrum (CSS; Greenstreet and Hall 1996, Rice and Gislason 1996, Duplisea et al. 1997, Greenstreet et al. 1999, Bianchi et al. 2000, Zwanenburg 2000). The CSS examines the relationship between abundance and size of animals in a community. In an exploited fish assemblage, larger fish generally suffer higher fishing mortality than smaller individuals; this may be one factor causing the size distribution to become skewed toward the smaller end of the spectrum (Zwanenburg 2000), and leading to a decrease in the slope of the size relationship over time with increasing fishing pressure. Similarly, k-dominance curves, which measure the combined dominance of the k most dominant species (Lambshead et al. 1983) in disturbed communities will differ from those in unperturbed communities (Rice 2000, Bianchi et al. 2000).

Existing NMFS bottom trawl survey data were used to create these indices (CSS slopes and heights and k-dominance curves) for the EBS ecosystem. A manuscript was produced and is in the internal review process. The manuscript is titled: "An investigation of fishing and climate effects on the community size spectra of eastern Bering Sea fish". This information was integrated into the Ecosystem Considerations report to provide a measure of ecosystem state and any potential effects of fishing. It was also presented at the ICES Annual Science Conference in Helsinki, Finland, September 17-21, 2007.

Unlike other marine ecosystems, the eastern Bering Sea CSS indicates that, overall, there has not been a linear decreasing trend in groundfish size or abundance over time; however, some time
series are variable and do show step-changes. We observed changes in the CSS slopes that suggest there were fewer small fish and more large fish in the 1990s. This pattern was primarily due to increases in Astheresthes spp., Hippoglossoides spp., rex sole, starry flounder, and skate biomass on the eastern Bering Sea shelf. Changes in CSS slopes and intercepts were not due to significant shifts in species composition, fishing intensity, or bottom temperature variability.

## Applications:

1. Use in single species stock assessments: Most single species groundfish stock assessments include an Ecosystem Considerations section that summarizes:
a. Ecosystem Effects on the stock:
i. Prey availability/abundance trends,
ii. Predator population trends,
iii. Changes in habitat quality, and
b. Fishery Effects on the ecosystem:
i. Fishery contribution to bycatch (prohibited species, forage fish, HAPC biota, marine mammals and birds, sensitive non-target species),
ii. Fishery concentration in space and time,
iii. Fishery effects on amount of large size target fish,
iv. Fishery contribution to discards and offal production,
v. Fishery effects on age-at maturity and fecundity.
2. Use in management decisions: In 2006, information provided in the Ecosystem Considerations report was used to reduce the ABC of walleye pollock. In the 2006 EBS pollock assessment, a precautionary ABC was set based on many sources of information from the ecosystem. The Scientific and Statistical Committee (SSC) noted: "The EBS stock remains above the MSY level, having declined from a peak in 2003 at a rate of about $19 \%$ per year. The decline is expected to continue until $2008, \ldots$ the series of low recruitments will result in an agestructure that is dominated by only a few year-classes, which could increase fluctuations in the population."
"Other issues raised in the stock assessment suggest a need for further caution. There has been a northward shift of with some portion of the population into Russian waters. Russian catches have been high...there has been a large decline in zooplankton, which is important in providing forage for juvenile pollock, and there has been increasing predation by arrowtooth flounder on juvenile pollock, which could contribute to further declines in adult pollock biomass."
"Consequently, the SSC agrees with the Plan Team that a reduction in ABC from the maximum permissible is justified."
3. Use in a Fishery Ecosystem Plan: The North Pacific Fishery Management Council appointed a Team to produce an Aleutian Islands (AI) Fishery Ecosystem Plan (FEP). The goal of the FEP is to provide enhanced scientific information and measurable indicators to evaluate and promote ecosystem health, sustainable fisheries, and vibrant communities in the Aleutian

Islands region. The FEP is intended to be an educational tool and resource that can provide the Council with both an 'early warning system', and an ecosystem context to decisions affecting the Aleutian Islands area. The AI FEP Team utilized information and indicators presented in the Ecosystem Considerations report and also suggested improvements or new indicators that could be used to improve the assessment of important interactions in the AI (http://www.fakr.noaa.gov/npfmc/current_issues/ecosystem/AIFEP507.pdf). In collaboration with AI FEP Team scientists, efforts to produce and improve AI indicators in the Ecosystem Considerations report have begun. Part of these efforts include requesting that contributing authors break out the AI from the Bering Sea as well as include some new AI-specific indicators in the report. Two indicators were added: 1. Pot fishing effort in the AI, and 2. Eddies in the AI. There was also an AI-specific climate summary added to the North Pacific Climate contribution. Some improvements recommended by the AI FEP Team included the Ecosystem Considerations reports include: 1. Forage -AI (relative mean CPUE and frequency of occurrence of forage species), 2. Miscellaneous species -AI (relative mean CPUE and frequency of occurrence of miscellaneous species), 3. HAPC Biota -AI (relative mean CPUE and frequency of occurrence of HAPC species), 4. Trophic level of the catch in the AI, and 5. Pelagic trawl fishing effort in the AI. Additionally, a contribution examining the distribution of rockfish species along environmental gradients in the Gulf of Alaska and Aleutian Islands bottom trawl surveys was added to the report. It is expected that in future drafts we will be incorporating more of the AI FEP- recommended indices.

## Publications/Presentations/Webpages:

## 1. Peer reviewed publications

## a. In progress

Boldt, J.L., and C.N. Rooper. In review. Juvenile Pacific ocean perch abundance, condition, diet and potential links to pelagic habitat in two areas of the Aleutian Islands. Submitted to Fishery Bulletin.
Boldt, J.L., S. Bartkiw, P.A. Livingston, G..Hoff, G. Walters. In internal review. An investigation of fishing and climate effects on the community size spectra of eastern Bering Sea fish.
Buckley, T.W., A. Greig, and J.L. Boldt. In internal review. Describing summer pelagic habitat over the continental shelf in the eastern Bering Sea, 1982-2006. Prepared for the NOAA Technical Memorandum Series.

## b. In print

Armstrong, J.L, K.W. Myers, D.A. Beauchamp, N.D. Davis, R.V. Walker, JL. Boldt, J.J. Piccolo, L.J. Haldorson, J.H. Moss. In press. Interannual and Spatial Feeding Patterns of Hatchery and Wild Juvenile Pink Salmon in the Gulf of Alaska in Years of Low and High Survival. Trans. Am. Fish. Soc.
Beauchamp, D.A., A.D. Cross, J. Armstrong, K.W. Myers, J.H. Moss, J.L. Boldt, and L.J. Haldorson. 2007. Bioenergetic Responses by Pacific Salmon to Climate and Ecosystem Variation. North Pacific Anadromous Fish Commission Bulletin 4:257-268.
Kline, T.C. Jr., J.L. Boldt, E.V. Farley Jr., L.J. Haldorson, J.H. Helle. 2008. Pink salmon (Oncorhynchus gorbuscha) marine survival rates reflect early marine carbon source dependency. Progr. In. Oceanogr. 77: 194-202.

Mueter, F.J., J. Boldt, B.A. Megrey, and R.M. Peterman. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. Can. J. Fish. Aquat. Sci. 64(6): 911-927.
Rooper, C.N, J.L. Boldt, and M. Zimmermann. 2007. An assessment of juvenile Pacific ocean perch habitat use in a deepwater nursery, Alaska. Estuarine, Coastal, and Shelf Sciences 75: 371-380.

## 2. Non peer reviewed publications

Boldt, J.L. (Editor and contributor) 2007. Ecosystem Considerations for 2008. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

## 3. Website

a. A website, which was developed to provide easy access to the Ecosystem Considerations report, individual contributions in the report, and data time series, was updated.
Ecosystem Considerations website: http://access.afsc.noaa.gov/reem/ecoweb/index.cfm

## 4. Presentations

1. Index development and ecosystem monitoring. Oral presentation. FATE annual meeting, San Jose, CA, August 27-28, 2007.
2. Indicators of size diversity in the eastern Bering Sea. Oral presentation. ICES Annual Science Conference, Helsinki, Finland, September 17-21, 2007.
3. Ecosystem Considerations for 2008. Oral presentation. Department of Fisheries \& Oceanography Working Group meeting, to review the State of the Pacific Ocean during 2007, Nanaimo, B.C., February 25, 2008.
4. Index development and ecosystem monitoring. Oral presentation. FATE annual meeting, La Jolla, CA, August 13-14, 2008.

## Literature Cited in this Report

Bianchi, G., H. Gislason, K. Graham, L. Hill, X. Jin, K. Koranteng, S. Manickchand-Heileman, I. Paya, K. Sainsbury, F. Sanchez, and K. Zwanenburg, 2000. Impact of fishing on size composition and diversity of demersal fish communities. ICES J. Mar. Sci., 57:558-571.
Cury, P.M., and V. Christensen. 2005. Quantitative ecosystem indicators for fisheries management: an introduction. ICES J. Mar. Sci. 62:307-310.
Duplisea, D.E., S.R. Kerr, and L.M. Dickie, 1997. Demersal fish biomass size spectra on the Scotian Shelf, Canada; species replacement at the shelfwide scale. Can. J. Fish. Aquat. Sci. 54:1725-1735.
Elliot, M. 2002. The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. Mar. Poll. Bull. 44:iii-vii.
Greenstreet, S.P.R. and S.J. Hall, 1996. Fishing and the groundfish assemblage structure in the northwestern North Sea: an analysis of long-term and spatial trends. J. Anim. Ecol. 65:577-598.
Greenstreet, S.P.R., F.E. Spence, J.A. McMillan, 1999. Fishing effects in northeast Atlantic shelf seas: patterns in fishing effort, diversity and community structure. V. Changes in
structure of the North Sea groundfish species assemblage between 1925 and 1996. Fish. Res. 40:153-183.
Hall, S.J., J.S. Collie, D.E. Duplisea, S. Jennings, M. Bravington, and J. Link. 2006. A lengthbased multispecies model for evaluating community responses to fishing. Can. J. Fish. Aquat. Sci. 63: 1344-1359.
Kruse, G.H., P. A. Livingston, J.E. Overland, G.S. Jamieson, S. McKinnell, and R. I. Perry. (eds). 2006. Report of the PICES/NPRB Workshop on Integration of Ecological Indicators of the North Pacific with emphasis on the Bering Sea. PICES Scientific Report No. 33, 109p.
Lambshead, P.J.D., H.M. Platt, and K.M. Shaw, 1983. The detection of differences among assemblages of marine benthic species based on an assessment of dominance and diversity. J. Nat. Hist. 17:859-874.
Mueter, F.J., J. Boldt, B.A. Megrey, and R.M. Peterman. 2007. Recruitment and survival of Northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. Can. J. Fish. Aquat. Sci. 64(6): 911-927.

National Research Council (NRC). 1998. Sustaining marine fisheries. A report of the Committee on Ecosystem Management for Sustainable Fisheries. Ocean Studies Board, Commission on Geosciences, Environment and Resources, National Research Council. Washington, D.C. National Academy Press, 167 pp.
Rice, J. and H. Gislason. 1996. Patterns of change in the size spectra of numbers and diversity of the North Sea fish assemblage, as reflected in surveys and models. ICES J. Mar. Sci., 53:1214-1225.
Rice, J.C., 2000. Evaluating fishery impacts using metrics of community structure. ICES J. Mar. Sci., 57:682-688.
Rodionov, S.N. 2005. A brief overview of the regime shift detection methods. To be presented at the ROSTE-UNESCO workshop "Regime Shifts and the Recovery in Aquatic Ecosystems: Challenges for Management Toward Sustainability", 12-17 June 2005, Varna, Bulgaria.
Rodionov, S.N., and J.E. Overland. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. ICES J. Mar. Sci. 62:328-332.
Wespestad, V.G., L. W. Fritz, W. J. Ingraham, Jr., and B. A. Megrey. 2000. On relationships between cannibalism, climate variability, physical transport and recruitment success of Bering Sea walleye pollock, Theragra chalcogramma. ICES. J. Mar. Sci. 57(2):272-279.
Wilderbuer, T. K, A. B. Hollowed, W.J. Ingraham, Jr., P. D. Spencer, M.E. Conners, N. A. Bond, and G. E. Walsters. 2002. Flatfish recruitment response to decadal climatic variability and ocean conditions in the Eastern Bering Sea. Progr. Oceanog. 55(1-2):235247.

Zwanenburg, K.C.T. 2000. The effects of fishing on demersal fish communities of the Scotian shelf. ICES J. Mar. Sci. 57:503-509.

07-05
Project Title: Developing recruitment forecasts for age structured flatfish stock assessments in the eastern Bering Sea based on models of larval dispersal

## Principal Investigators:

William Stockhausen, Thomas Wilderbuer, Janet Duffy-Anderson, Albert Hermann

## Goals:

A 2-dimensional, wind-driven, surface current only model (OSCURS) currently provides a qualitative index of annual recruitment for winter-spawning flatfish on the eastern Bering Sea shelf. The principal goal of this project is to develop quantitative recruitment indices and forecasts for two of these flatfish, northern rock sole and Alaska plaice, based on more detailed behavioral models for early life stages and patterns of 3-dimensional advective transport in the eastern Bering Sea. A secondary goal is to demonstrate the utility of these indices/forecasts in age-structured stock assessment models for these species. The quantitative recruitment indices should provide an alternative to, and improvement on, the current qualitative indices.

## Approach:

Our approach to achieve the principal goal of the project is to use a coupled biophysical individual-based model (DisMELS: Dispersal Model for Early Life Stages) that incorporates ontogenetic changes in early life history parameters and simulates egg and larval dispersal under 3-dimensional oceanographic currents to predict relative fluctuations in annual recruitment due to density-independent, advective processes on the eastern Bering Sea shelf. DisMELS uses stored output of 3-dimensional oceanographic currents, temperature and salinity fields at daily time steps from a Regional Ocean Modeling Systems (ROMS) oceanographic model for the northeast Pacific Ocean to simulate advective transport of pelagic eggs and larvae. Simulated individual eggs or larvae (in the case species with of demersal eggs, such as northern rock sole) are released along the bottom throughout a pre-defined "spawning area" during the spawning season. Individuals are tracked through time and space using Lagrangian particle tracking "with behavior"; i.e., individuals are allowed to undergo vertical migration: they actively swim up or down in the water column until they enter a "preferred" depth range (different ranges can be defined for daytime and nighttime, allowing diurnal migration to be incorporated). Individual growth and mortality can also be tracked. Ontogenetic changes in vertical migration behavior, as well as growth or mortality rates, can be incorporated in the model by defining a series of life history sub-stages that individuals progress through: different model parameters for different sub-stages yield ontogenetic changes in behavior, growth, and/or mortality. Individuals reaching the final larval sub-stage metamorphose into a "settlement-competent" stage that can "settle" to the benthos upon reaching pre-defined juvenile "nursery" habitat. Individuals in the settlement stage that do not reach suitable nursery habitat before the stage terminates (a pre-set amount of time) are regarded as having died. A relative index of annual recruitment is generated by simulating thousands of individuals over one model year and calculating the fraction that are transported from the spawning areas to the nursery areas and successfully settle for that year. A time series for this recruitment index is generated by running the model for multiple years. The "skill" of this index can be assessed by comparing it with recruitment estimates from current stock assessment models.

To incorporate the resulting indices within the appropriate stock assessments, our approach is to modify the existing stock assessment models for Alaska plaice and northern rock sole to accommodate the annual recruitment indices as, effectively, recruitment surveys. The assessment models will be modified to incorporate an additional likelihood component that allows the assessment model to "fit" the recruitment indices.

## Work Completed:

Work has been ongoing in the following project areas: acquiring ROMS oceanographic model output for the eastern Bering Sea, processing previously-collected egg and larval samples, improving the DisMELS model capabilities. In addition, we have generated an initial set of recruitment indices for Alaska plaice and northern rock sole based on preliminary runs of the DisMELS model. We have not yet modified the appropriate assessment models to incorporate the DisMELS-based recruitment indices, but will complete those modifications within the next year.

## ROMS output acquisition

ROMS 3-dimensional oceanographic model results were acquired at $\sim 10 \mathrm{~km}$ resolution and a daily time step for the eastern Bering Sea during the time period 1979-2004 from prior runs of the NEP4 ROMS model at the Alaska Region Supercomputing Center. The resulting dataset is ~300 GB.

## Egg/larval sample processing and data analysis

All data for Alaska plaice egg, larval, and juvenile distributions collected under the EcoFOCI program at the Alaska Fisheries Science Center were examined, analyzed statistically, and graphically plotted. Maps of distribution were generated, and growth rates were estimated using back-calculations based on lengths. Data were summarized seasonally and interannually, and were provided for modeling efforts. Data included: vertical distribution, growth rate, duration of time in plankton, seasonality of occurrence, purported spawning areas, presumed drift trajectories, and presumed juvenile habitat areas. A manuscript is in preparation (see below) that describes and summarizes the results of the field investigations on Alaska plaice.

Data on northern rock sole larvae and juveniles recently collected under the EcoFOCI were also analyzed to support modeling efforts. Data included seasonality of occurrence of larvae and juveniles (no egg data available), growth rate, vertical distribution, horizontal distribution, and juvenile (age-0) collections.

These data were used, in part, to determine initial DisMELS parameter values for preferred diurnal depth ranges, growth rates, spawning areas and nursery habitats for species-specific model simulations.

## DisMELS model development

The DisMELS modeling framework has undergone substantial revision and improvement to facilitate multiple-year simulations, calculation of spatial patterns of connectivity between spawning and nursery areas, and visualization of results. Model classes representing adult and settlement-competent life stages were developed and incorporated within the modeling framework. Creation of the "adult" class simplified the process of "injecting" simulated pelagic eggs or larvae into the model throughout extended spawning seasons and during model runs that extend over multiple model years. Creation of the "settlement-competent" class allowed more
biological realism to be incorporated within the model with regard to the transition from the pelagic environment to the benthos for juvenile flatfish.

## Preliminary model results

We have completed preliminary model runs to generate recruitment indices covering 19792004 for both northern rock sole and Alaska plaice. Sample results from the northern rock sole model runs are illustrated in Fig.s 1-6. Unfortunately, an initial comparison of the resulting indices with estimates of recruitment from the corresponding stock assessment models is rather unfavorable (Fig.s 7-8). Potential factors leading to the poor performance, such as inappropriate temporal and spatial scales in the oceanographic model, are currently being investigated.

## Applications:

None yet. We regard the DisMELS recruitment results (see above) as preliminary at this point. Thus, we have not yet provided them to the appropriate stock assessment authors as an alternative to the OSCURS-based qualitative recruitment indices.

## Publications/Presentations/Webpages:

Publications
Duffy-Anderson, JT, MJ Doyle, KL Mier, PJ Stabeno and TK Wilderbuer. In prep. Early life ecology of Alaska plaice (Pleuronectes quadrituberculatus) in the eastern Bering Sea: seasonality, distribution, and dispersal. Submission to Journal of Sea Research.

## Presentations

Stockhausen, WT, JT Duffy-Anderson, TK Wilderbuer and AJ Hermann. 2008. Can different early life history strategies explain different recruitment patterns for two flatfish species in the eastern Bering Sea? Presentation at the 2008 Larval Biology Symposium, Lisbon, July 2008.


Figure 1. Tracks of 10,000 simulated northern rock sole larvae over a 120 day period for model year 1982. Tracks are color-coded by sub-stage: preflexion larvae--gold; post-flexion larvae--red; competent-to-settle juveniles--cyan. Final locations are indicated by the dark blue dots.


Figure 2. Map of the final locations of the individuals shown in Fig. 1, color-coded by the area in which each was "spawned". Spawning areas are denoted colored polygons numbered 1-6. Thus, e.g., individuals that were spawned in area 6 (blue polygon) are also colored blue.


Figure 3. Map of the starting locations of the individuals shown in Fig. 1, color-coded by the area in which each found suitable nursery habitat (depth shallower than 50 m , polygons 1-19) and "settled". Thus, e.g., individuals that settled in area 18 (pink polygon) are also colored pink. Black dots represent the starting location of individuals that never reached suitable nursery habitat.


Figure 4. Plot of the connectivity matrix between the spawning areas ("source" polygons) and nursery areas ("sink" polygons) from Fig. 1. Colors represent the fraction of individuals originating from a "source" polygon that settled in a "sink" polygon.


Figure 5. Plot from the preliminary northern rock sole model of the fraction of individuals from all spawning locations by nursery area ("sink" polygon) for all model years. The plot indicates substantial interannual variability in both settlement area and strength.


Figure 6. Plot from the preliminary northern rock sole model of the total fraction of individuals that reached appropriate nursery areas, by model year.


Figure 7. Comparison of the preliminary DisMELS recruitment index for northern rock sole (log-transformed and standardized) with z-scores from fitting a stock-recruit model to spawning biomass and recruitment estimates from the 2007 northern rock sole stock assessment model. The correlation between the two time series is -0.27 .


Figure 8. Comparison of the preliminary DisMELS recruitment index for Alaska plaice (log-transformed and standardized) with z-scores from fitting a stock-recruit model to spawning biomass and recruitment estimates from the 2007 Alaska plaice stock assessment model. The correlation between the two time series is -0.20 .

07-06
Project Title: Impact of freshwater and terrestrial ecosystem conditions on estuarine dependent and anadromous fish

Principal Investigators: Steve Lindley and Steve Ralston NMFS Southwest Fisheries Science Center, Eric Danner University of California Santa Cruz

## Goals:

The primary goal of our project is to develop ecosystem indicators for stock assessment based on cross-ecosystem exchange between terrestrial, freshwater, and marine systems, and to make these indicators available to fisheries researchers in an easy to use, spatiotemporally explicit, web-based database.

## Approach:

Most ecosystem indicators for marine fish stock assessment are generated from physical and biological oceanographic measurements and models that do not capture important terrestrial and freshwater influences on estuarine dependent and anadromous fish life cycles. We developed a comprehensive database of ecosystem indicators for watersheds draining into the coastal ocean of California by spatially synthesizing a wide range of diverse data sets. While many of these data are currently available through various sources, they have not been summarized in a format that is relevant for fisheries research, nor are they standardized and consolidated in a single location.

## Work Completed:

We have developed a working database of terrestrial and freshwater ecosystem indicators for all coastal California watersheds draining into the CCLME. Users can select a basin and generate data summaries for a wide range of variables using a simple interactive menu. Examples of the indices include (summarized by basin): water flow, air temperature, monthly heat index, soil water content, snow cover, gross primary production, percent landcover (by land class), percent impervious surface, percent canopy cover, and toxicity or water quality index. CO-I S. Ralston then used the flow data for the Sacramento-San Joaquin River Delta to extend the starry flounder stock assessment model and develop a long-term reconstruction of abundance.

## Applications:

Our work has the potential to have significant benefit to marine resource management by providing data that was previously unavailable or difficult to obtain at the necessary spatial scales. The indicators that we have developed and summarized are important to estuarine dependent or anadromous life cycles. At the most general level, they will be useful for detecting trends in terrestrial and freshwater ecosystems that might be important for understanding changes in the structure and function of the CCLME.

## Publications/Presentations/Webpages:

Ralston et al. A long-term reconstruction of starry flounder abundance by inclusion of estuarine conditions and year-class strength. In prep.

Project Title: The Phenology of Coastal Upwelling in the California Current

## Principal Investigators:

Steven Bograd and Daniel Palacios, NOAA Southwest Fisheries Science Center, Environmental Research Division; William Sydeman, Farallon Institute for Advanced Ecosystem Research; Scott Benson, NOAA Southwest Fisheries Science Center, Protected Resources Division; Mark Carr and Mark Readdie, University of California, Santa Cruz.

## Goals:

Many marine organisms have life histories adapted to seasonal events in the environment. Changes in the amplitude and phasing (i.e., phenology) of seasonally varying processes can therefore significantly affect the functioning of marine ecosystems, from primary producers to fish stocks to apex predators (Cushing, 1990; Beare and McKenzie, 1999; Bograd et al., 2002; Logerwell et al., 2003; Abraham and Sydeman, 2004). Such phenological effects are potentially disruptive to trophic interactions, perhaps more so than those associated with interannual climate events and decadal climate shifts (Stenseth et al., 2002; Sydeman et al., 2006; Barth et al., 2007). Assessments of marine ecosystem response to climate change will need to consider potential changes in the seasonal cycle of the dominant physical processes that drive ecosystem structure and productivity (Hunt et al., 2002; Durant et al., 2007).

The objective of this project was to develop simple indices to quantify variation in the timing of the onset of coastal upwelling in the California Current (i.e., the date of the "spring transition" to seasonal upwelling conditions), the temporal evolution and overall intensity of upwelling, and the duration of the upwelling season, as well as the spatial variations of these properties along the West Coast between Baja California and Vancouver Island. We also investigated interannual variability in the characteristics of coastal upwelling in the California Current over the period 1967-2007. Operational indicators of upwelling phenology could provide an early warning signal to resource managers of the probability of a disruption to the CCLME.

## Approach:

We developed indices that build upon and expand the utility of the historical Upwelling Index (UI; Bakun, 1973). Since upwelling has a cumulative effect on ecosystem productivity and structure, we derived the cumulative upwelling index (CUI), based on integrating the mean daily upwelling index from January $1^{\text {st }}$ to the end of the year. We used the 41 -year time series (19672007) of daily UI at six locations along the U.S. West Coast, from $33^{\circ} \mathrm{N}$ to $48^{\circ} \mathrm{N}$, separated by $3^{\circ}$ latitude, to develop several indicators characterizing the phase and amplitude of California Current upwelling.

## Work Completed:

Based on the CUI, we defined within-season indices of the date of the spring transition, intensity and evolution of upwelling, and duration of the upwelling season from the 41-year CUI series at each location as described below, and shown schematically in Figure 1.
(1) Spring Transition Index (STI): The date (Julian Day) on which the CUI, integrated from January $1^{\text {st }}$, reaches its minimum value, i.e., the date after which positive UI (upwelling) prevails.

Similarly, the end date of the upwelling season (END) is defined as the date on which the CUI reaches its maximum value. The date on which the rate of change of CUI is greatest (MAX) we define as the date of peak seasonal upwelling.
(2) Length of Upwelling Season Index (LUSI): The total number of days between the observed start date (STI) and observed end date (date of maximum CUI) of the upwelling season.
(3) Total Upwelling Magnitude Index (TUMI): The total CUI integrated from the observed spring transition date (STI) to the observed end date of the upwelling season. This is a measure of the intensity of coastal upwelling integrated over the entire length of the defined upwelling season.
(4) Total Downwelling Magnitude Index (TDMI): The total CUI integrated from the observed end date of the upwelling season (END) to the observed spring transition date (STI) the following year. This is a measure of the intensity of downwelling


Figure 1: Climatological annual cycle of CUI, showing derived phenological indices. between subsequent upwelling seasons.

We have used this set of indicators to describe meridional and temporal variability in the characteristics of coastal upwelling in the California Current (Figure 2). These indices reveal extended periods of strong (1970s, 1998-2004) and weak upwelling (1980-1995) and a trend towards a later and shorter upwelling season in the northern CCLME. El Niño years were characterized by delayed and weak upwelling in the central CCLME. Understanding the causes and ecosystem consequences of phenological changes in coastal upwelling is critical, as climate models project significant variability in the amplitude and phase of coastal upwelling under varying climate change scenarios. These results are described in Bograd et al. (2008).

Finally, we have related these intra-seasonal and interannual variations in upwelling to responses at several trophic levels, focusing on the reproductive success of one planktivorous (Cassin's auklet) and one pisciverous (common murre) seabird species that breed on the Farallon Islands. The dates of egg laying for both species are highly correlated with indices of coastal upwelling, with a lag of 2-3 months. This implies that a pre-conditioning of the system by early (late winter) upwelling events yields an earlier mean egg-laying date, and hence higher reproductive success. These results are described in Schroeder et al. (2008).

## Applications:

The set of physical indicators developed here are the first to address the critical issue of phenology in the California Current, and will contribute to our understanding of climateecosystem interactions in the CCLME. Although still largely in research-development-validation mode, these indices are being correlated with a variety of long-term biological time series. These
indices will become part of subsequent Integrated Ecosystem Assessments (IEAs) of the California Current Ecosystem, and will be made available to NMFS scientists and managers for implementation into stock-specific and ecosystem-based assessment models.

Figure 2: Time vs. latitude diagrams for (a) spring transition index (Julian day), (b) length of upwelling season index (days), and (c) total upwelling magnitude index $\left(\mathrm{m}^{3} \mathrm{~s}^{-1} 100 \mathrm{~m}^{-1}\right)$.

## Publications/Presentations:



Bograd, S.J., I. Schroeder, N. Sarkar, X. Qiu, W.J. Sydeman, and F.B. Schwing, 2008. The phenology of coastal upwelling in the California Current, Geophysical Research Letters, submitted.

Schroeder, I., W.J. Sydeman, S.J. Bograd, N. Sarkar, and F.B. Schwing, 2008. Phenological indicators of seabird reproductive success in the California Current, Marine Ecology Progress Series, submitted.

Bograd, S.J., The phenology of coastal upwelling in the California Current. PICES $16{ }^{\text {th }}$ Annual Meeting, Victoria, BC, October 2007.

Bograd, S.J., The phenology of coastal upwelling in the California Current. IEP Annual Workshop, Pacific Grove, CA, February 2008.

Schroeder, I., Phenological indicators of seabird reproductive success in the California Current. FATE Annual Science Meeting, August 2008.

## References:

Abraham, C.L. and W.J. Sydeman (2004), Ocean climate, euphausiids and auklet nesting: interannual trends and variation in phenology, diet and growth of a planktivorous seabird, Ptychorampus aleuticus. Mar. Ecol. Prog. Ser., 274, 235-250.
Bakun, A. (1973), Coastal upwelling indices, West Coast of North America, 1946-71. NOAA Tech. Rep. NMFS SSRF-671, 114 pp.
Barth, J.A., B.A. Menge, J. Lubchenco, F. Chan, J.M. Bane, A.R. Kirincich, M.A. McManus, K.J. Nielsen, S.D. Pierce, and L. Washburn (2007), Delayed upwelling alters nearshore coastal ecosystems in the northern California Current, Proc. Natl. Ac. Sci., 104(10), 3719-3724.
Beare, D.J., and E. McKenzie (1999), Connecting ecological and physical time series: the potential role of changing seasonality. Mar. Ecol. Prog. Ser., 78, 307-309.
Bograd, S., F. Schwing, R. Mendelssohn, and P. Green-Jessen (2002), On the changing seasonality over the North Pacific. Geophys. Res. Lett., 29(9), doi:10.1029/2001GL013790.
Cushing, D.H. (1990), Plankton production and year-class strength in fish populations: an update of the match-mismatch hypothesis. Adv. Mar. Biol., 26, 249-293.
Durant, J.M., D.O. Hjermann, G. Ottersen and N.C. Stenseth (2007), Climate and the match or mismatch between predator requirements and resource availability. Clim. Res., 33(2), 271-283.
Hunt, G.L., Jr., P. Stabeno, G. Walters, E. Sinclair, R.D. Brodeur, J.M. Napp, and N.A. Bond (2002), Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep-Sea Res. II, 49, 5821-5853.
Logerwell, E.A., N. Mantua, P.W. Lawson, R.C. Francis, and V.N. Agostini (2003) Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (Oncorhynchus kisutch) marine survival. Fish. Oceanogr., 12, 554-568.
Stenseth, N.C., A. Mysterud, G. Ottersen, J.W. Hurrell, K.S. Chan, and M. Lima (2002), Ecological effects of climate fluctuations. Science, 297, 1292-1296.
Sydeman, W.J., R.W. Bradley, P. Warzybok, C.L. Abraham, J. Jahncke, K.D. Hyrenbach, V. Kousky, J.M. Hipfner, and M.D. Ohman (2006), Planktivorous auklet (Ptychoramphus aleuticus) responses to the anomaly of 2005 in the California Current. Geophys. Res. Lett., 33, L22S09, doi:10.1029/2006GL026736.

07-08
Project Title: Incorporation of ocean environmental variation in the Klamath River fall Chinook (KRFC) salmon stock assessment

## Principal Investigators:

Brian Wells/UCSC, Michael Mohr/SWFSC/FED, Masami Fujiwara/UCSC, and Churchill Grimes/SWFSC/FED

## Goals:

We aim to improve the current KRFC ocean stock abundance forecast model by incorporating environmental variables. This could constitute a significant improvement in the Pacific Fisheries Management Council's (PFMC) ability to manage KRFC salmon harvest, and will improve the justification for highly restrictive ocean salmon fishery regulations off the coasts of California and Oregon, when required based on the KRFC abundance forecast. We also have the goal of determining the vital rates that are most dramatically affecting variability around the current forecast models.

## Approach:

Environmental data included three-month averaged seasonal estimates of sea surface temperature, sea level height, curl, upwelling, wind stresses, spring transition date, and Klamath River flow obtained from the Northern California region (Cape Mendocino, CA to Cape Blanco, OR). Salmon abundance data was obtained from annual reports of the PFMC and maturation rate data was obtained from the California Department of Fish and Game.

Path analysis- Path analysis was used to determine the direct, indirect, and total effects of a suite of environmental variables on ocean abundance. A path analysis begins with the variables of interest arranged in a hierarchical fashion representing the demonstrated causative relationships between variables (e.g. wind stresses drive, in part, upwelling) and/or accumulated variance (e.g. sea level height represents the accumulated variance of many factors including upwelling and wind stresses). Given an a priori defined path structure, successive stepwise regressions are then used to test the significance of the relationships between the variables and, hence, the paths. It is important to note that while path analysis quantifies the degree of colinearity between variables, it does not correct for it.

Partial least squares regression (PLS)- PLS is an extension of multiple regression that is appropriate for identifying a relationship between a dependent variable and a large set of independent variables When an ordinary multiple regression analysis includes many independent variables, colinearity among them often becomes a problem. PLS regression circumvents this problem by finding orthogonal sets of linear combinations of independent variables in the order of decreasing correlation with the dependent variable and retaining the significant linear combinations (latent variables) in the model. In this analysis, we used the residuals from the ordinary linear regression current forecasting model as a dependent variable and the significant environmental variables selected in the path analysis as independent variables.

Generalized Additive Models (GAMS)- As an alternative to the path and partial least squares regression analysis, we evaluated GAMS. GAMS are attractive in that the original environmental variables, as opposed to linear combinations of the variables, are preserved in fitted models, and this facilitates interpretation of the results.

The combination of these three approaches allowed us to build predictive models that allowed for mechanistic interpretation of the links between salmon dynamics and the environment. We also repeated the above methodologies to determine the likelihood that the environment relates to early or late maturity of males which would directly impact the sibling model regressive approach (i.e., variability in the maturation rate would translate to variability in the relationship between ocean abundance estimates and age 2 returns).

## Work Completed:

The primary focus of the Fisheries and the Environment program is to promote research that can be directly used to incorporate environmental variation into fishery stock assessments and management. We have demonstrated that by incorporating a multivariate environmental factor into the current age 3 ocean abundance forecast model that there is a moderate improvement in model fit (improvement from $R^{2}=0.44$ to $R^{2}=0.78$ ) for the 1993-2007 period. Figure 1 demonstrates the effectiveness of this new hybrid model.


FIGURE 1: Grey line represents age 3 ocean abundances 1993-2007. Orange line represents estimates from the current sibling model and blue line represents estimates from the hybrid model developed in this project. Dashed lines represent the mean square errors of prediction. Orange and blue arrows point to years when the sibling and hybrid models failed to fit the observed ocean abundance, respectively.

Examination of the GAMS used to develop these models indicate that error around the current sibling model can be attributed to variability in vital rates during the second year at sea; the year of the age 2 return on which the age 3 ocean abundance forecast is based. Specifically, second year spring and summer values of sea level height, sea surface temperature, and curl were negatively correlated to error around the sibling model. When sea level height, sea surface temperature and curl increased, as is indicative of poorly productive conditions, age 3 ocean abundance was overforecast. However, as upwelling during the second year spring and summer improved the sibling model underforecast age 3 ocean abundance.

Variability in the sibling model is due to variability in the age 2 maturation rate and variability in age 3 natural mortality. That second year environment is the most highly correlated factor to residual variability about the sibling model leads us to suspect that the vital rate most altered by the environment in later life (that after the first year mortality) is early maturation of males. Specifically, an environment representative of poor ocean production in the second winter and spring (i.e., decreased upwelling, increased river flow, and later transition to an upwelling season) leads to a higher maturation rate of age 2 males. This is supported by results of cohort reconstruction analyses of coded-wire tagged fish from Iron Gate and Trinity River hatcheries.

It is worth noting that we attempted these approaches to improve age 4 abundance estimates with limited success. Little was gained toward improving forecasting by including environmental variables into the model.

## Applications:

The forecast model we have developed for the ocean abundance of KRFC age 3 salmon is promising for application in that the model appears to fit the historical data better than the current sibling-only forecast model that is currently used for the KRFC stock assessment. Whether this model offers improved predictive power over the current forecast model, however, remains to be determined. We have used this same modeling approach to model the abundance of Central Valley Chinook salmon and these results, although preliminary, also appear promising and are currently being considered by a NMFS interagency workgroup that is examining the potential causes for the recent decline of certain west coast salmon stocks.

## Publications/Presentations/Webpages:

Wells, B.K., J. Field, M. Fujiwara, C. Grimes, B. MacFarlane, M. Mohr, and M. O'Farrell. 2008. Examination of the effects of environmental variability on cohort dynamics of Central Valley and Klamath River, California Chinook salmon. Salmon Ocean Ecology Symposium, Nanaimo, CAN.

Wells, B.K. 2008. Effects of climate change in marine environment on salmonid populations. Invited presentation to the Protected Resources Division Workshop.

Wells, B.K. 2008. Untangling the relationships between variability in the marine environment, populations dynamics, and community structure. Invited seminar to NOAA Fisheries Ecology Division.

Wells, B.K. 2008. California Current large marine ecosystem recent conditions, trend, and forecasting: Southern CA Current. Interagency Salmon Decline Working Group.

07-09
Project Title: Incorporating environmental forecasts into stock assessments and stock assessment decision tables

Principal Investigators: Michael J. Schirripa / Northwest Fisheries Science Center, Richard Methot / Office of Science and Technology, C. Phillip Goodyear / Consultant, Research Assistant (TBD) / Oregon State University-Cooperative Institute of Marine Resource Studies (CIMRS)

Goals: Recruitment of the U.S. west coast sablefish (Anoplopoma fimbria) has been shown to be influenced by changes in the environment (Schirripa and Colbert 2006). Attempts to model this influence were made in most recent sablefish stock assessment (Schirripa 2007). The objective of this study was to use simulation techniques to test the efficacy of two competing methods of including the observed environmental influence into the sablefish stock assessment and determine the accuracy and precision of each. Our overall goal to arrive at an objective evaluation of the to methods and to make a determination as to which should be used in future assessment.

We also proposed to develop decision tables in which the various states of nature are represented not by various parameter values, but by various assumptions with regard to the future productivity of the ocean environment. We were to assume the "base case" model for each state of nature as the best choice to represent the stock dynamics and utilize forecasts from the time series analysis to develop the various assumptions regarding the possible future productivity of the U.S. west coast as represented by SSH . Where possible, we were to investigate using other existing forecasts and/or leading indicators to formulate assumptions of the states of nature. Ultimately we wanted to use forecasts of the states of nature that we can assign some sort of quantitative probability to, a value that is often difficult to arrive at when using various parameter values as is currently done. Furthermore, rather than assigning one probability to an entire assumed state of nature, we were to make attempts at finding ways of assigning annual probabilities based on the confidence of the forecast values. In the end, we did not intend for this work to replace the existing decision table design, but rather to compliment them by offering a different perspective on how to view the forecasts

Approach: We used simulation techniques to create a population of fish whose recruitment was modulated by a known environmental effect; "assessed" the population using the two methods described above, and compared the estimated productivity values and management benchmarks to the true values in an effort to discover if any biases and/or inaccuracies were associated which of the two methods.

We simulated a simple fishery system consisting of a single fishery with data available annually on total catch and age, length, and size-at-age composition; and a single survey that provided estimates of annual stock biomass and age, length, and size-at-age compositions. In all cases the data were generated the simulated random data in such a manner that they would be unbiased and we gave the SS2 program the true parameter values as the initial values with which to begin its iterative search for the set of maximum likelihood parameter estimates. The resulting estimates of parameter values and management benchmarks were compared to known values
from the simulations. We used the age-structured population model described in Goodyear (1989); its application in the context of MSY estimation is described in (Goodyear 1996); and other tests of estimation methods (e.g. Prager, et.al. 1996, Prager and Goodyear 2001, Goodyear, 2007). We added a variable to simulate cyclical variability in survival from egg to recruitment associated with temporal variations in the environment. The simulation model is implemented monthly with one sex and includes environmental effects on the mean survivorship of age-0 recruits.

Work Completed: We successfully completed the population simulation portion of this work. We found that, under the circumstances simulated in this study, the particular method (scheme 6) that resulted in the most accurate estimations of the selected parameters (the details of "scheme $6 "$ are too extensive to include here, please refer to the manuscript). Scheme 6 also resulted in the greatest overall percent error in the estimation of spawning stock biomass; however this error was only about 5 percent. There are circumstances where the "data" method is more clearly superior to the "model" method. For instance, in situations where the environmental data may be incomplete the years of missing values would necessarily need to be assumed to have a value of zero, which will be interpreted as a valid data point representing no deviation for that year. The data method, on the other hand, would merely skip this year and allow that year's recruitment deviation to be fit to the remaining observation data sources. In this regard, the best modeling approach would be dictated by the data at hand rather than the model.

There was one major caveat that should be noted. This study was designed to simulate the particular biology and assessment of sablefish of the Pacific west coast of the continental United States, an eastern boundary upwelling system. As such, the results may be associated the particular annual patterns of the sea surface index of this system and may not be fully applicable to all situations. To arrive at a more universal recommendation with regard to which scheme was truly the best, a more extensive study that includes various annual environmental patterns, which is beyond the scope of this work, would need to be conducted. It is likely that, even with a more extensive examination of environmental patterns, that one singles scheme may not be found to the best choice for all situations. For this reason we conclude that in order to find the best scheme for a particular assessment problem, a set of simulations similar to those outlined here be conducted, using the actual data sets being considered within that particular assessment problem. Nonetheless, it is quite possible that the climatological and oceanographic processes indexed by the actual sea surface height could index the productivity of the California Current System in general and thus modulate other important biological process that could modulate recruitment success in other commercially important species in this ecosystem, either directly or indirectly.

The simulation portion of this work took longer than expected. This was due, mostly, to our CIMRS research assistant unexpectedly vacating their position with us early in the process. Attempts were made at refilling the position but the available applicants were few and did not immediately possess the skills necessary to carry out the proposed work. Consequently, the principal investigator was left to complete the vast majority of the work on their own. For this reason, the work proposed with regard to the decision tables and environmental forecasts was not completed.

Applications: This work has lead to improvements and modifications to both the FSIM simulation model as well the SSv3 operating model. These methods will be discussed and used in the next sablefish stock assessment due in 2011. However, results will be applicable to all other stock assessments using environmental data due in 2009. Furthermore, we now have a completely seamless connection between a detailed, independent simulator and the most used stock assessment model on the west coast. This tool will enable countless similar simulation studies that should continue to result in improvements to the Stock Synthesis model. We have already passed this work on to the Stock Synthesis post-doc that in turn has modified our code to work with the most recent version of Stock Synthesis (SSv3).

## Publications/Presentations/Webpages:

1. Western Groundfish Conference. Feb. 2008 (oral presentation)
2. National Stock Assessment Workshop. May, 2008 (oral presentation)
3. Climate Change and its Effects on the World's Oceans. June 2008 (oral presentation with a manuscript submitted to ICES Journal as proceedings)

## Literature Cited

Goodyear, C. P. 1989. LSIM: A length-based fish population simulation model. National Oceanic and Atmospheric Administration, Technical Memorandum NMFS-SEFC-219, Washington, D.C.

Goodyear, C. P. 1996. Variability of fishing mortality by age: Consequences for MSY. North American Journal of Fisheries Management 16:8-13.

Prager, M. H., C. P. Goodyear, and G. P. Scott. 1996. Application of a surplus production model to a swordfish-like simulated stock with time-changing gear selectivity. Transactions of the American Fisheries Society 125:729-740.

Prager, M. H., C. P. Goodyear. 2001. Effects of Mixed-Metric Data on Production Model Estimation: Simulation Study of a Blue-Marlin-Like Stock. Transactions of the American Fisheries Society 130:927-939.

Schirripa, M.J.. 2007. Status of the sablefish resource off the continental U.S. Pacific coast in 2005. Appendix B in Pacific Fishery Management Council. Status of the Pacific coast groundfish fishery through 2006 and recommended acceptable biological catches for 2008-09. Pacific Fishery Management Council, Portland, Oregon.

Schirripa, M.J. and J.J. Colbert. 2005. Interannual changes in sablefish (Anoplopoma fimbria) recruitment in relation to oceanographic conditions within the California Current System. Fish. Oceanogr. 14:4, 1-12

07-10
Project Title: Tree-ring techniques for age validation and establishing long-term effects of climate variability on the growth of Gulf of Mexico red snapper

Principal Investigators: Bryan Black, George Boehlert, Oregon State University, Newport, Oregon. Robert Allman, NOAA/NMFS Southeast Fisheries Science Center. Michael Schirripa, NOAA/NMFS Northwest Fisheries Science Center

## Goals:

For more than a century, red snapper (Lutjanus campechanus) has supported a fishery in the northern Gulf of Mexico and today remains the most economically important species of the snapper/grouper complex from Florida to southern Texas (Collins 1887, Goodyear 1995). However, this history of heavy exploitation has significantly reduced populations, as evidenced from a decline in recreational landings from a high of 4.2 million pounds in 1980 to 1.4 million pounds by 1990 (Schirripa and Legault 1999). Since its first assessment in 1988, red snapper has been classified as over-fished, and to date populations have yet to show significant signs of recovery despite the implementation of management programs intended to rebuild the stock (Hood et al. 2007, Porch 2007, Schirripa and Legault 1999).

As a consequence of recent catch restrictions on red snapper, pressure may be increasing on other species, particularly gray snapper (Lutjanus griseus) (Fischer et al. 2005). This species overlaps in distribution with red snapper in the northern Gulf of Mexico and shares a preference for reefs and other hard-bottom substrates as adults (Hoese and Moore 1977). It now supports a large recreational fishery in the Gulf of Mexico that landed almost 2 million pounds in 2006, in addition to a smaller commercial fishery that landed 270 thousand pounds the same year (Personal communication from the National Marine Fisheries Statistics Division, Silver Spring, MD). Maximum ages for red and gray snapper as validated through bomb radio carbon $\left({ }^{14} \mathrm{C}\right)$ are 58 and 28 years, respectively, both sufficiently long to be particularly vulnerable to overfishing (Baker and Wilson 2001, Fischer et al. 2005). Due to increasing exploitation the Gulf of Mexico Reef Fish Stock Assessment Panel has recommended that gray snapper be considered for future stock assessment.

Despite levels of spawning stock biomass below historical standards, red snapper recruitment in the eastern and western Gulf of Mexico has generally exceeded the long-term average over the past twenty-five years (SEDAR 7 2005). In addition to this trend, red snapper recruitment is highly episodic, often varying by one or two orders of magnitude from year to year. Based on a much shorter recruitment time series, the same also appears to be true of gray snapper. Thus, these phenomena suggest that spawning stock biomass is not a strong predictor of recruitment strength, and that other variables are involved. One of the most likely candidates is climate, based on a number of other studies that have demonstrated a correspondence between recruitment and environmental variability (Hare et al. 1999, Hollowed et al. 2001). Though the majority of these studies involve fisheries of the North Pacific, the same may be true of red snapper in the northern Gulf of Mexico.

To better address the influence of climate variability on red and gray snapper, we relate climate indices to long-term estimates of recruitment and biomass. We also apply tree-ring (dendrochronology) techniques to develop indices of somatic growth from otolith ring widths. When implemented in rockfish of the northeast Pacific, chronologies spanned multiple decades, were annually resolved, of a quality comparable to that in tree-ring chronologies, and strongly
related to climate indices (Black et al. 2005, 2008a). If this technique could be successfully applied in the Gulf of Mexico, otolith chronologies would provide a unique data source for evaluating long-term growth patterns in red and gray snapper. Thus, the goals of this study are to $i$ ) implement tree-ring techniques to develop otolith growth chronologies, and ii) integrate chronologies with historical records to evaluate the interrelationships among somatic growth, biomass, recruitment, and climate in these snapper species.

## Approach:

From 1991 to 2007, red and gray snapper were sampled from recreational, commercial and fishery-independent landings from Louisiana to Florida. Sagittal otoliths were collected along with morphometric data including sex, length, and weight. Otoliths were thin-sectioned through the transverse plane with a high-speed saw to a thickness of 0.5 mm following the methods of Cowan et al. (1995). Exceptionally clear otoliths aged via annuli counts to be at least twenty years old for red snapper and fifteen years old for gray snapper were retained. For both red and gray snapper, growth increments were analyzed along the dorsal side of the sulcal groove. Red snapper otoliths were observed with reflected light while gray snapper otoliths were observed with transmitted light. All samples were viewed with a binocular dissecting microscope at 40x magnification.

In the first step of chronology development, otoliths growth increments were visually crossdated using the "list year" technique. The procedure is based on the principles that at least one climatic variable limits growth and values of these climatic variables fluctuate over time. Under such conditions, climatic variability induces synchronous growth patterns in all individuals within a given region. These synchronous growth patterns, much like bar codes, can then be cross-matched among samples to verify that all growth increments have been correctly identified and assigned the correct calendar year. In these otoliths, synchronous patterns were identified by noting growth increments that were conspicuously narrow or wide relative to immediately surrounding increments (Yamaguchi 1991). The process of crossdating began at the marginal growth increment, which is known to have formed at the calendar year of capture. From this dated increment, synchronous growth patterns were used to verify dates of successively earlier increments, ending with the innermost increment (Black et al. 2005). When all growth increments were correctly identified, years of especially narrow or wide increments corresponded among all specimens. Between these prominent years, less conspicuous yet synchronous growth patterns could be used to verify crossdating.

Once visual crossdating was complete, we photographed all samples with a Leica DC300 7.2 megapixel digital camera and then measured growth increment widths using the program ImagePro Plus v. 6.0 (Media Cybernetics, Silver Spring, Maryland). Growth increments were measured continuously from the dorsal distal margin to within three years of the focus, or as close to the focus as possible. The first three years of growth were excluded due to the rapidly changing geometry of the otolith. A total of two axes were measured per otolith, always following the direction of growth (i.e. perpendicular to the growth increments).

At each site, crossdating was statistically verified using the International Tree-Ring Data Bank Program Library program COFECHA, available thorough the University of Arizona Laboratory of Tree-Ring Research http://www.ltrr.arizona.edu/pub/dpl/ (Grissino-Mayer 2001). This program has been used to verify crossdating in Pacific rockfish species as well as Pacific geoduck, a long-lived marine bivalve (Black et al. 2008a, Black et al. 2008b, Black et al. 2008c). In summary, this procedure isolated high-frequency variability in each set of measurements via
the process of detrending, and then cross-correlating the detrended measurements to verify that all samples aligned with one another. Detrending was accomplished by fitting each set of otolith measurements with a cubic spline set at a $50 \%$ frequency response of 22 years (Cook and Peters 1981, Grissino-Mayer 2001), then dividing ring width measurements by the values predicted by the cubic spline. Any remaining autocorrelation was removed to ensure that all detrended time series met the assumptions of serial independence. Each detrended set of otolith measurements was then correlated with the average of all other detrended sets of otolith measurements in the sample. In so doing, the high frequency growth pattern of each individual was compared to the high frequency growth pattern of all other individuals. Isolating only the high frequency, serially independent growth pattern prevented spuriously high correlations among individuals, and also mathematically mimicked the process of visual crossdating.

Once crossdating verification was complete we began developing a master chronology for each site by detrending the original measurement time series with negative exponential functions. Negative exponential functions removed age-related growth declines while preserving any remaining low-frequency variability, much of which could have been induced by climate. For each species, all detrended series were then averaged into a master chronology (Cook 1985). All chronology development was conducted using the program ARSTAN (developed by Ed Cook and Paul Krusic; available at http://www.ldeo.columbia.edu/res/fac/trl/public/publicSoftware.html ) (Cook 1985). Once completed, the quality of the chronology was quantified using the Expressed Population Signal (EPS) statistic, which describes the strength of the synchronous growth pattern relative to growth patterns unique to individual samples (i.e. "noise"). Though there is no significant threshold for this statistic, an EPS value of 0.85 or greater is considered adequate by dendrochronologists for climate reconstruction, a level more than sufficient for the purposes of our study (Wigley et al. 1984).

Each snapper master chronology was correlated with monthly averages of the Pacific North American Oscillation Index (PNA), Mississippi River discharge, sea surface temperatures (SST), and the Multivariate El Niño Southern Oscillation Index (MEI). The MEI is the leading principal component of six marine and atmospheric variables in the tropical Pacific (1950-1994), obtained from the NOAA Climate Diagnostics Data Center
http://www.cdc.noaa.gov/people/klaus.wolter/MEI/ (Wolter and Timlin 1998). The PNA was obtained from the NOAA National Weather Service Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna index.html (Wallace and Gutzler 1981). Northern Gulf of Mexico sea surface temperatures were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and averaged between 28 and 30 degrees latitude, and from 83 to 90 degrees longitude, the approximate sampling locations of the fish used to develop the chronology. Monthly averages were used in the correlation analysis to determine the periods of the year in which environmental variability most strongly affected growth. To examine the relationship between growth and recruitment, growth chronologies were compared to juvenile red snapper indices of abundance from SEAMAP fishery-independent surveys conducted in the Gulf of Mexico from 1972 to 2003 (Turner and Porch 2004).

## Work Completed:

Red snapper and gray snapper exhibited similar synchronous growth patterns with the most pronounced signature years in 1996, 1993, 1987, 1978 (narrow) and 1999, 1990, 1982, and

1979 (wide). In comparison to red snapper, contrast between opaque and hyaline zones was much greater and annuli were much narrower for gray snapper. However, gray snapper otolith clarity substantially diminished south of approximately $28^{\circ}$ latitude, restricting the sample range for this species to the northeastern Gulf of Mexico (Figure 1). Otolith clarity was more consistent across the northern Gulf of Mexico for red snapper; however, the oldest individuals in the otolith collections were concentrated off the coast of Louisiana. Growth pattern western Gulf of Mexico otoliths were unique, and for this reason, we retained only those samples obtained from the eastern Gulf of Mexico (Figure 1).

All otolith measurement time series showed distinct age-related growth declines (Figure 2A,B). However, gray snapper individuals shared more high-frequency growth synchrony than did red snapper, as reflected by a higher series intercorrelation (Table 1). Mean sensitivity was also greater in gray snapper, indicating greater fluctuations in growth from year to year (Table 1). A higher series intercorrelation and mean sensitivity may reflect the superior clarity of gray snapper otoliths. A large degree of growth variability was also shared between species, as reflected by the fact that the two master chronologies positively and significantly correlated ( $r=$ $0.68 ; p<0.001$ ) with one another (Figure 2C). Such a high degree of synchrony among individuals and between species suggests that red and gray snapper growth is strongly affected by environmental variability.

The red and gray master chronologies both significantly correlated to indices of environmental variability (Figure $3 \mathrm{~A}, \mathrm{~B}$ ). Correlations were strongest for gray snapper, especially for March and April sea surface temperatures (Figure 3B). This chronology also showed significant relationships with MEI during the prior summer and fall and only weakly associated with February and March Mississippi River discharge (Figure 3B). Correlation patterns were quite similar for red snapper, though much less pronounced (Figure 3A). Overall, these climate-growth relationships suggest that warm and wet conditions during the winter and early spring months favor growth for red and gray snapper. The mechanisms behind these relationships are difficult to interpret, though favorable growing conditions in the winter months may extend the growing season, leading to the formation of the relatively large annual growth increment. A positive correlation with Mississippi River discharge may also indicate a fertilization effect from increased nutrient input, or may be an artifact of the increased precipitation that would occur in years with warmer sea surface temperatures. What is particularly remarkable, however, is the strength of the relationship with MEI, especially for gray snapper. These correlations can be explained by the tendency of warm, wet (cool, dry) conditions in the northern Gulf of Mexico to occur during La Nina (El Nino) years. Negative correlations with MEI, in which negative (positive) values indicate La Nina (El Nino) events, would be expected if relatively warm, wet years favor snapper growth.

Red snapper recruitment patterns also relate to environmental variability and in much the same manner as the red and gray snapper growth chronologies (Figure 3C). Recruitment is positively related to sea surface temperatures, especially in the winter and spring months, and is negatively related to the MEI in the summer and fall prior to the growing season (Figure 3C). One difference between recruitment and the growth chronologies is that recruitment is negatively related to MS River discharge, and this relationship with discharge occurs during November and December rather than February and March (Figure 3). Recruitment is also negatively related to prior May and June sea level (correlation -0.54), a variable not significantly related to either growth chronology. Yet in general, climate-growth relationships closely match those of the snapper chronologies, especially gray snapper. Considering this overlap, the gray snapper
chronology positively and significantly relates to red snapper recruitment (Figure 4). The relationship with the red snapper chronology is also positive, but much weaker with an $R^{2}$ of 0.03. Red snapper recruitment may better relate to the gray snapper chronology due to the fact that gray snapper otoliths are much clearer and almost certainly provided a higher quality chronology, and that gray snapper collection sites were located farther east in the Gulf of Mexico, better overlapping with the area sampled for red snapper recruits. Overall, these results suggest that the environmental conditions favorable to snapper growth are also favorable for recruitment, and that these favorable conditions are defined by La Nina events in the Pacific prior to the growing season and warm waters in the winter and spring of the growing season.

In addition to understating species' response to environmental variability, climate-growth relationships may also provide some degree of predictive power. In a stepwise regression ( $\alpha=$ 0.05 to enter) for those variables that most strongly correlated with the red snapper master chronology (the average of March through April SST and the average of December and January MEI), only the SST variable was selected for inclusion in a model for a total $R^{2}$ of $0.26 ; p=$ 0.005 . For the gray snapper master chronology, variables considered were the average of March and April SST and the average of June through August MEI, and once again SST was the only variable included ( $R^{2}=0.39 ; p=0.0002$ ). Finally for red snapper recruitment, variables considered were average annual SST, the average of prior May and June sea level, and the gray snapper master chronology. The final two-variable model included the SST and sea level variable for a total $R^{2}$ of $0.47 ; p=0.0001$. Both variables had variance inflation factors of 1.11 and Mallow's Cp was 3.0, indicating good model stability. The gray snapper master chronology could not explain a significant level of remaining variance in recruitment. However, climate variables do appear to afford at least some ability to predict growth and recruitment in these species.

In conclusion, growth increment chronologies provided a means by which to link somatic growth, recruitment, and climate in red and gray snapper. Environmental variability significantly affects growth and reproduction in this species, particularly in the winter and spring months, a time of year that is also particularly important in rockfish of the northeast Pacific (Black et al. 2005, 2008a). Growth is also related to recruitment, but to a lesser extent than climate. Indeed just two climate variables explain almost half the variance in red snapper recruitment, and such close relationships suggest that climate could serve as a tool for predicting future levels of recruitment based on observational data or climate model forecasts. Ultimately, we believe that these techniques will be relevant to other species in the Gulf of Mexico, potentially allowing for more integrated analyses involving multiple species or communities.

## Literature Cited

Baker, M.S., and Wilson, C.A. 2001. Use of bomb radiocarbon to validate otolith section ages of red snapper Lutjanus campechanus from the northern Gulf of Mexico. Limnology and Oceanography 46(7): 1819-1824.
Black, B.A., Boehlert, G.W., and Yoklavich, M.M. 2005. Using tree-ring crossdating techniques to validate annual growth increments in long-lived fishes. Can J Fish Aquat Sci 62(10): 2277-2284.
Black, B.A., Boehlert, G.W., and Yoklavich, M.M. 2008a. A tree-ring approach to establishing climate-growth relationships for yelloweye rockfish in the northeast Pacific. Fish Oceanogr: In press.

Black, B.A., Colbert, J.J., and Pederson, N. 2008b. Relationships between radial growth rates and lifespan within North American tree species. Ecoscience In Press.
Black, B.A., Gillespie, D., MacLellan, S.E., and Hand, C.M. 2008c. Establishing highly accurate production-age data using the tree-ring technique of crossdating: a case study for Pacific geoduck (Panopea abrupta). Can J Fish Aquat Sci: In press.
Collins, J.W. 1887. Notes of the red snapper fishery. Bulletin of the United States Fish Commission 6: 299-300.
Cook, E.R. 1985. A Time-Series Analysis Approach to Tree-Ring Standardization. Thesis (Ph.D.), University of Arizona, Tucson, AZ.
Cook, E.R., and Peters, K. 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bulletin 47: 45-53.
Cowan, J.H., Shipp, R.L., Bailey, H.K., and Haywick, D.W. 1995. Procedure for Rapid Processing of Large Otoliths. Transactions of the American Fisheries Society 124(2): 280-282.
Fischer, A.J., Baker, M.S., Wilson, C.A., and Nieland, D.L. 2005. Age, growth, mortality, and radiometric age validation of gray snapper (Lutjanus griseus) from Louisiana. Fish Bull 103(2): 307-319.
Goodyear, C.P. 1995. Red snapper in U.S. waters of the Gulf of Mexico. National Marine Fisheries Service, Southeast Fisheries Science Center, Miami Laboratory, Miami, Florida.
Grissino-Mayer, H.D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res 57(2): 205-221.
Hare, S.R., Mantua, N.J., and Francis, R.C. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries 24(1): 6-14.
Hoese, H.D., and Moore, R.H. 1977. Fishes of the Gulf of Mexico, Texas, Louisiana, and adjacent waters. Texas A\&M University Press, College Station.
Hollowed, A.B., Hare, S.R., and Wooster, W.S. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. Progress in Oceanography 49(1-4): 257-282.
Hood, P.B., Strelcheck, A.J., and Steele, P. 2007. A history of red snapper management in the Gulf of Mexico. American Fisheries Society, Symposium 60, Bethesda, Maryland.
Porch, C.E. 2007. An assessment of the red snapper fishery in the U.S. Gulf of Mexico using a spatially-explicit age-structured model. American Fisheries Society, Symposium 60, Bethesda, Maryland.
Schirripa, M.J., and Legault, C.M. 1999. Status of the red snapper in U.S. waters of the Gulf of Mexico: updated through 1998, Miami, Florida.
SEDAR 7. 2005. Southeast Data Assessment and Review. Stock assessment report of SEDAR 7: Gulf of Mexico red snapper, Charleston, South Carolina.
Turner, S.C., and Porch, C.E. 2004. Alternative indices of abundance of juvenile red snapper from the Gulf of Mexico from SEAMAP surveys 1972-2003.
Wallace, J.M., and Gutzler, D.S. 1981. Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter. Monthly Weather Review 109(4): 784-812.
Wigley, T.M.L., Briffa, K.R., and Jones, P.D. 1984. On the average value of correlated timeseries, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteo 23(2): 201-213.

Wolter, K., and Timlin, M.S. 1998. Measuring the strength of ENSO events - how does 1997/98 rank? Weather 53: 315-324.
Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. Can J Forest Res 21(3): 414-416.

Table 1. Red and gray snapper chronology properties.

| chronology | sample <br> size | mean <br> sensitivity | interseries <br> correlation ${ }^{\text {c }}$ | mean series <br> length (years) |
| :--- | :---: | :---: | :---: | :---: |
| red snapper | 30 | 0.13 | 0.54 | 15.4 |
| gray snapper | 24 | 0.18 | 0.76 | 17.1 |



Figure 1. Map of the study area with collection sites for red snapper and gray snapper.


Figure 2. Measurements of otolith growth increment widths for A) red snapper and B) gray snapper individuals. C) Master chronologies for red and gray snapper.


Figure 3. Correlations between climate variables and the (A) red snapper and (B) gray snapper master chronologies as well as C) log-transformed red snapper recruitment index for the eastern Gulf of Mexico. Climate indices are Mississippi River discharge (MS River), the Multivariate ENSO Index (MEI), and sea surface temperatures (SST). Each chronology is correlated with monthly averages of each environmental variable for each month of the current year, as well as each month lagged (L) by one year.


Figure 4. Relationship between the gray snapper master chronology and log-transformed red snapper recruitment index for the eastern Gulf of Mexico.

## Applications:

The crossdated snapper chronologies will have several applications related to fishery management:

1. The master chronology will serve as an age validation tool, which could be used for establishing highly accurate recruitment histories. Once the final chronology is complete, additional fish caught in the region may be crossdated against it. In the process of crossdating the correct calendar year may be assigned to each growth increment, including the innermost increment formed at the year of birth, thereby establishing an exact age (see Black et al. 2005, Canadian Journal of Fisheries and Aquatic Sciences. 62:2277-2284). Otoliths validated by crossdating can also be used for training tools for new age readers.
2. The chronology provides long-term perspectives on growth of the red and gray snapper in the Gulf of Mexico, also allowing for a comparison of growth patterns across species.
3. The chronologies quantify the effects of climate variability on growth, which are considerable. The preliminary chronology indicated that the SST and MEI have strong influences on growth. Positive growth can be expected under warm conditions in the Gulf of Mexico, and the MEI may offer some predictive ability as to snapper growth in the coming year.
4. Recruitment appears to be strongly influenced by climate variability. For red snapper, recruitment is associated with warm conditions in the Gulf of Mexico, as is growth. Such information will be of use to fishery managers, helping to account for recruitment variability over time.
5. The fact that somatic growth and recruitment are interrelated to one another as well as to climate underscores the sensitivity of this species to environmental variability. Climate should be carefully considered in management of this species, and interpreting, and potentially forecasting, the dynamics of the fishery.

## Publications/Presentations/Webpages:

The results of this study and other FATE-related studies have been the focus of the following presentations over the past year.

Presentations by BA Black:
Fisheries and the Environment Annual Conference. August, 2008. La Jolla, CA.
Relationships among growth, recruitment, and climate in rockfish from the Gulf of Maine and Gulf of Mexico
Keynote address, The First American Dendrochronology Conference, June 2008. Vancouver, BC. State of the Science: Sclerochronology: Application of tree-ring techniques in marine and freshwater ecosystems
NOAA National Marine Fisheries Service, Southeast Fisheries Science Center, April 2008. Panama City, FL. Growth increment analysis as a tool for comparing diverse taxa and ecosystems in the Pacific Northwest.
NOAA National Marine Fisheries Service, Alaska Fisheries Science Center, March 2008. Seattle, WA. Growth increment analysis as a tool for comparing diverse taxa and ecosystems in the Pacific Northwest.
$15^{\text {th }}$ Western Groundfish Conference, February 2008. Spatial and temporal variability in growth of yelloweye rockfish in the northeast Pacific

Presentation by Robert Allman:
The First American Dendrochronology Conference, June 2008. Vancouver, BC. Otolith chronology development and climate-growth relationships for red snapper (Lujanus campechanus) in the northern Gulf of Mexico.

The following FATE-related manuscript is in press:
BA Black, GW Boehlert, and MM Yoklavich. 2008. Establishing climate-growth relationships for yelloweye rockfish in the northeast Pacific using a dendrochronologial approach. Fisheries Oceanography In press

The following manuscript was inspired by FATE research in rockfish. Here we have applied the tree-ring technique of crossdating to generate highly accurate age data for Pacific geoduck.

BA. Black, D Gillespie, SE MacLellan, and CM. Hand. 2008. Establishing highly accurate production-age data using the tree-ring technique of crossdating: a case study for Pacific geoduck (Panopea abrupta). Canadian Journal of Fisheries and Aquatic Sciences In press.

The following publication, which quantifies the relationship between growth rate and lifespan (i.e. within species slower-growing individuals live longer) was inspired by FATE-research. This growth and lifespan relationship is a concern in fisheries, and I took this idea and applied it to trees, for which there is a much larger growth-increment database.

BA Black, JJ Colbert, and N Pederson. 2008. Relationships between lifespan and radial growth rate within North American tree species. Ecoscience. In Press 15(3), September 2008.

The following FATE-related publication is in review
BA Black. Climate-driven linkages between marine and terrestrial ecosystems in western North America. Marine Ecology - Progress Series

## FATE projects initiated in FY 2008

08-01 Development of biological and physical indices for stock evaluation in the Dry Tortugas pink shrimp fishery - Joan Browder and Michael Parrack (NMFS-SEFSC), Maria Criales, Claire Paris and Laurent Cherubin (Univ. Miami)

08-02 Predictors for larval transport success and recruitment for cod in the Gulf of Maine James Churchill and Loretta O'Brien (WHOI), Jeffery Runge (Univ. Maine), Jim Manning (NMFS-NEFSC)

08-03 Developing ecological indicators for spatial fisheries management using ocean observatory defined habitat characteristics in the Mid-Atlantic Bight - John Manderson (NMFSNEFSC), Josh Kohut (Rutgers Univ.), Matthew Oliver (Univ. Delaware)

08-04 An integrated assessment of the physical forcing and biological response of the pelagic ecosystem of the northern California Current, focused on coastal pelagics and salmon - Bill Peterson and Robert Emmett (NMFS-NWFSC)

08-05 Not all climate forecasts are created equal: How precise and/or accurate do they need to be to be useful to stock assessments? - Michael Schirripa (NMFS-NWFSC), Richard Methot (NMFS-S\&T), C. Phillip Goodyear (Oregon State Univ.-CIMRS)

08-06 Developing statistically robust IPCC climate model products for estuarine-dependent and anadromous fish stock assessments - Frank Schwing, Steve Lindley, Roy Mendelssohn and Steve Ralston (NMFS-SWFSC), Eric Danner and Bruno Sanso (Univ. California Santa Cruz), Jim Overland (OAR-PMEL), Muyin Wang (Univ. Washington-JISAO)

08-07 Integrating indicators: co-variation, periodicity and amplitude of key biological signals from central Oregon and northern California - William Sydeman, Alec MacCall, Kyra Mills and Julie Thayer (Farallon Inst.), Steven Bograd and Frank Schwing (NMFS-SWFSC), Chet Grosch (Old Dominion Univ.)

