Evaluating the mechanisms underlying distribution shifts and age-truncation in Silver hake (*Merluccius bilinearis*) survey data

Megan O'Connor[1], James Churchill[2], David Richardson[1],
[1] - Northeast Fisheries Science Center;
[2] - Department of Physical Oceanography, Woods Hole Oceanographic Institution

BACKGROUND

Silver hake (*Merluccius bilinearis*) are a commercially important semi-pelagic fish distributed from Newfoundland to South Carolina. In U.S. waters annual silver hake landings peaked at 350,000 mt in the mid-1960s but have since declined to an average of ≈8,000 mt over the last decade. Landings on the Scotian Shelf in Canadian waters experienced a similar peak, of 300,000 mt, in the early 1970s but have remained at 13,000 mt over the past decade. Currently, the U.S. manages silver hake as separate northern and southern stocks, with the northern flank of Georges Bank as the dividing line (Almeida 1987, Bolles and Begg 2000). This stock structure has frequently been questioned in the assessment process, and recent assessments have also evaluated a single U.S. silver hake stock. However, the single stock models have not been accepted. Canada manages silver hake on the Scotian Shelf as a separate stock.

In U.S. waters, management advice for silver hake is currently based on the survey index method using NEFSC bottom trawl survey data. This method concluded that both silver hake stocks in U.S. waters are not overfished and that overfishing is not occurring. During the 2011 assessment, an age-structured model was also developed using the Age Structured Assessment Program (ASAP). This model run was not accepted by the review panel as it was felt that there was not a consistent and coherent explanation for the simultaneous increases in the survey index and truncation of age-structure in the survey and fishery given that landings were at historically low levels and diet data did not show a substantial increase in natural mortality (NEFSC 2011). Changes in the assumed shape of the selectivity curve used in the assessment drastically changed the perception of the status of the stock and the magnitude of SSB in recent years. The review panel suggested further work on a variety of topics to address the seeming contradictions in the age-structure data and survey indices. Included on the list of topics was the potential for age-structured changes in the distribution of silver hake in response to environmental variability.

Many marine fish in the Northeast United States continental shelf ecosystem have experienced changes in distribution due shifts in ocean temperature which may be linked to climate change (Nye et al. 2009). Changes in distribution could affect population or stock structure and thus impact the management and assessment of these species (Link et al. 2011). The mean center of biomass of the southern stock of silver hake in U.S. waters on the spring trawl survey has shifted northward over the past 40 years, whereas the northern stock distribution has remained stable. This northward shift in the southern stock is correlated with changes in basin scale oceanographic processes, in particular the position of the northern wall of the Gulf Stream offshore of the U.S. continental shelf (Nye et al. 2009, Nye et al. 2011).

Extensive research off the Pacific coast of North America has also revealed substantial interannual changes in the distribution of Pacific hake (*Merluccius productus*), a congener of silver hake. Interestingly, the conceptual framework used to evaluate distribution changes in Pacific hake differs notably from that used to evaluate silver hake. The majority of Pacific hake off the west coast of North America are included within a single migratory stock that spawns off southern and central California and ranges 20° latitude to waters as far north as Alaska. In

contrast, each silver hake stock is assumed to range only 3-6° latitude. Much smaller populations of Pacific hake also occur in select nearshore areas. Analyses show that the northward migration of Pacific hake in the summer is affected by temperature (Dorn 1995), as is suggested for the southward extent of silver hake migration in the winter (Nye 2011). However, older and larger Pacific hake have also been shown to make more extensive northward migrations whereas smaller fish migrate less and remain in the southern end of their range (Fig. 1). The age-structure of the population in any one year can thus be a dominant factor determining the northward extent of the summer migration (O'Connor and Haltuch, in prep). The effect of population age-structure on the southern extent of the winter migration of silver hake has not been evaluated. Furthermore, northward extensions of spawning, and in turn juvenile nursery grounds, have also been observed during certain times for Pacific hake (Benson et al. 2002). For silver hake the effect of changing environmental conditions on spawning locations and juvenile nursery areas has not been considered.

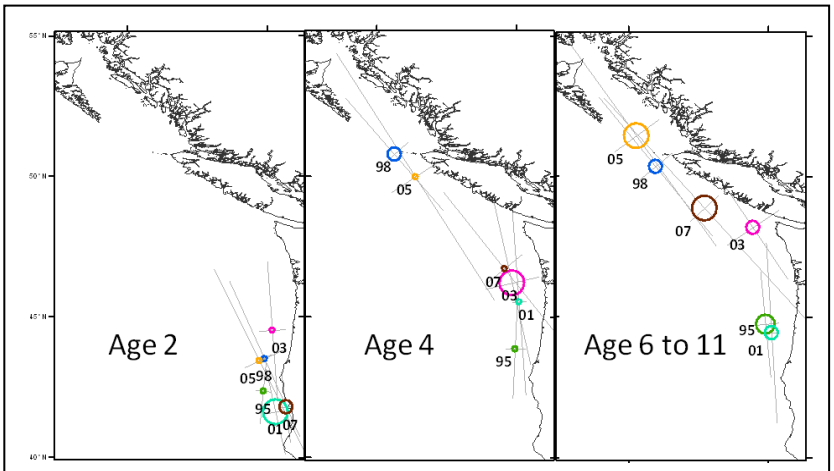

Figure 1. The mean spatial location (circles) and variance (grey lines) of each age group and survey year of Pacific. Circle size is proportional to biomass.

APPROACH

We propose a life-stage specific analysis of the mechanisms underlying shifts in the distribution of silver hake. Previous work has clearly documented a shift in the center of biomass of silver hake sampled on the northeast shelf on the spring trawl survey (Nye et al. 2011). The intent of our analysis is to evaluate whether this shift is consistent across life stages (larvae, juveniles, adults) and between summer spawning and the winter southerly migration. Overall, our intent is to integrate analyses of larval and adult silver hake in order to evaluate, not just the shifts in silver hake, but also the seeming contradictions in the available adult/juvenile data and stock structure data that continue to cause problems for age-structured assessments.

Specific Objectives

1) Two factors may simultaneously be responsible for the observed northward shift in silver hake center of biomass on the NEFSC spring trawl survey. Larger silver hake are hypothesized to migrate further south in the winter, and thus the truncation of silver hake age-structure observed on the trawl survey since the mid-1980s could have shifted the population center of biomass northwards independent of changes in the environment. However, temperatures across the shelf have also warmed over this time period. We will employ spatially-explicit regression models to assess the joint effects of temperature and age-structure on silver hake populations on the northeast shelf. The intent is to partition the cause of the silver hake distribution change into environmental and age-structure related factors.
2) Peak silver hake spawning occurs in late July, five months after the reported shifts in distribution on the spring trawl survey. Shifts in the spatial distribution of silver hake

spawning have not been analyzed. We will use sampled larval distribution data and a particle tracking model to back calculate silver hake spawning distribution, and will evaluate the factors underlying any observed shifts in spawning location.

3) Interannual variability in spawning distribution and in current patterns can affect the relative proportion of silver hake larvae transported to different potential juvenile nursery grounds on the northeast shelf. Since juvenile hake tend to have restricted migrations, changes in settlement areas may affect the distribution of 1-2 year old fish. We will use the particle tracking model to predict the settlement locations of silver hake in different time periods given observed larval distributions and year-specific modeled current patterns.

Objective 1: Age-specific distribution modeling—Silver hake age-specific distribution will be calculated using the center of biomass and variance procedure presented in Woillez et al. (2007) using NEFSC trawl survey for each age from 1972 (the first year age data is available) to the present (e.g. analysis in Fig. 1 for Pacific Hake). A spatially explicit regression analysis, outlined in Bartolino et al. (2011), will then be used to model the joint effects of temperature and age structure on adult silver hake distribution. Models will be built under two scenarios: high adult hake abundance on the survey (1960s to 1985) and low adult hake abundance on the survey (1986 to present). Model calculations will be used to predict annual relative abundance and distribution under varying temperature and age structure regimes. For example, we will predict the distribution of silver hake given 1960s age structure and 2000s temperature to evaluate to the hypothesis that environmental factors have reduced the catchability of silver hake by shifting hake distribution. Comparisons will also be made between relative and observed abundance and distribution estimates though a hold-out cross validation modeling procedure.

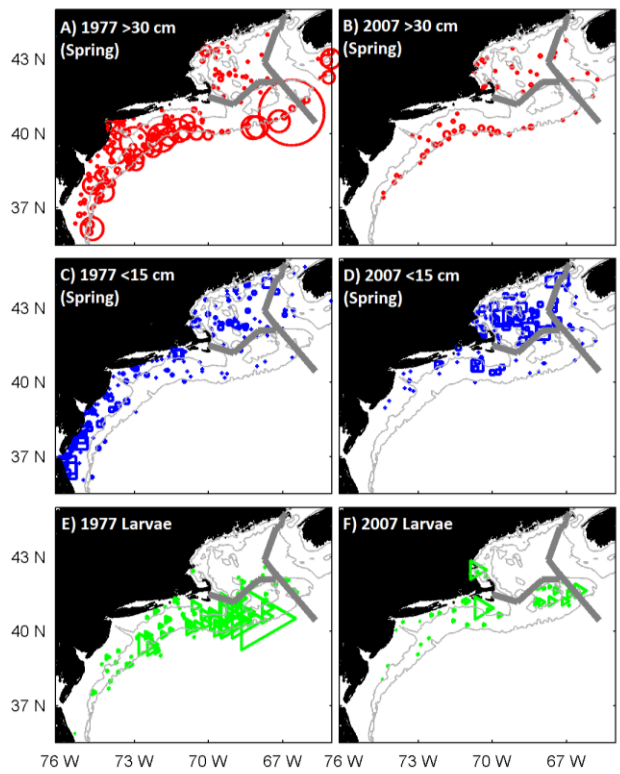

Figure 2. Distribution plots of silver hake on the NEFSC trawl survey A,B) mature adults, C,D) juveniles, and E,F) larvae in 1977 and 2007. Stock dividing lines in grey. Note the more substantial shift in juvenile relative to adult distribution and the substantial reduction in adult abundances.

Link et al. (2010) provides framework for examining the mechanisms of changes in fish stock spatiotemporal distributions that include conceptualizations of stock dynamics. Our model results will be interpreted using this framework by examining environmental and life history effects on the spatial dynamics of silver hake and evaluating the validity of the current two-stock structure.

Objective 2: Spawning distribution**—**Estimated spawning distributions will be calculated using larval distributions from the Ecosystem Monitoring (EcoMon: 1999-present) and Marine Resource Monitoring Assessment and Prediction (MARMAP: 1977-1987) cruises and numerical modeling to track larvae to their point of origin. The particle/larval tracking model was developed as part of a previously funded FATE project (Churchill et al., 2011) and has since been optimized. It utilizes hydrodynamic data generated by the Finite Volume Coastal Ocean Model (FVCOM) applied to the coastal ocean off the northeast U.S. coast (extending in space from the Scotian Shelf to the Chesapeake Bay mouth, and in time from 1978 to the present). Outputs from the FVCOM model (e.g. velocities and temperatures) are accessed through the OPeNDAP model data archive maintained by US Geological Survey Woods Hole Field Office (http://www.necodp.org/committees/modeling-committee/gulf-of-maine-model-interoperability-pilot-project/index.html).

A procedure to estimate the relative magnitude of spawning across space given observed larval distributions at age was developed as part of a previous FATE project focused on Atlantic herring (Hare et al. 2011). This procedure is currently being tested and optimized. This analytical technique fits predicted abundance-at-age of larvae across a set of sampling stations to the actual observed abundance-at-age of larvae. Predicted abundance-at-age are based on 1) a defined relative spawning magnitude across a grid of particle release locations and 2) larval trajectories from that grid of release locations. By minimizing the difference between the observed and predicted age-specific larval distributions, the relative magnitude of spawning in each grid cell is estimated. It's noteworthy that this technique uses larval paths tracked forward in time to estimate larval spawning locations. As opposed to the alternative approach of backtracking larvae from observed collection locations, this method allows for the inclusion of larval behavior and sub-model-grid scale diffusion. Our use of this technique with Atlantic herring resulted in predicted spawning locations that were consistent with the independent acoustic survey of spawning herring and herring spawning habitat (i.e. hard bottom).

The center of egg production will be calculated from the estimated spawning distributions, determined from the technique described above, for each year of the EcoMon and MARMAP surveys. Water column temperatures, which were measured on each of these cruises, will be related to spawning distributions. Interestingly, summer sea surface temperatures on the northeast shelf have increased at a faster rate than winter temperatures (Friedland and Hare, 2007). We hypothesize that a poleward shift in spawning occurs during years with warm summers. We also hypothesize, on a decadal-scale, that the magnitude of the shift in spawning in summer exceeds the northward shift in adult silver hake on the spring trawl survey due to the more pronounced summer warming (Objective 1).

Objective 3: Juvenile nursery grounds**—**In addition to using larval tracking to estimate spawning locations (Objective 2), we will forward track silver hake larvae to presumed juvenile nursery grounds. Larval silver hake tend to be concentrated in 1) Southern New England 2) the southern flank of Georges Bank and 3) in the western Gulf of Maine (Fig. 2). In the spring the majority of silver hake spawned the previous summer and fall (considered Age-1 fish) occur in two locations 1) the Gulf of Maine and 2) Southern New England waters from New Jersey to Rhode Island. Juvenile growth rate differ between these nursery areas. Age-1 silver hake are nearly absent from Georges Bank.

We will implement the same particle tracking code used in Objective 2 to forward track larvae from observed collection locations. Larval silver hake are pelagic for ≈3 months and larval age-length relationships are available (Jeffrey and Taggart 2000). Based on observed larval

distributions each year we will predict the relative magnitude of juveniles in each nursery locations. These predictions will be compared to sampled juvenile abundances the following spring on the trawl survey (7 months after spawning). We hypothesize that a northward shift in spawning has shifted the nursery area for silver hake from Southern New England to the Gulf of Maine. This range shift mechanism is different from individual juvenile fish actively tracking concurrent temperatures.

TIMELINE

Year 1-Develop spatially explicit distribution model and initial larval tracking analyses.
Year 2-Integration of larval and juvenile/adult analyses and evaluation of hypothesized mechanisms for distribution shifts and biases in survey indices.

BENEFITS

Two notable challenges have faced silver hake stock assessments for >10 years. First, contradictory data exists on the nature of stock-structure in this species, and recent assessments have considered both two and one stock scenarios. Second, age-structured assessments produce strong and unexplained residual patterns in fitting the abundance-at-age data, and there is uncertainty as to whether the absence of large fish in the trawl surveys is real or if there is an alternate explanation. Research recommendations from the assessment process have included: 1) "*investigate spatial distribution, stock structure, and movements .. in relation to physical oceanography*" and 2) "*try to ascertain better the reasons for the scarceness of larger/older fish."* Our proposal targets these two research recommendations by evaluating age-specific and life-history specific (spawning, southerly migration) changes in the distribution of silver hake, and the mechanisms that underlie these changes. The extensive research on Pacific hake distribution provides a useful comparative framework for this research, one that has not previously been applied to silver hake. One PI (O'Connor) was recently involved in Pacific hake research.

The intent of our analysis is to inform the interpretation of available survey data. For example, a larval index was presented at the prior assessment, but was not included in modeling exercises due to the absence of CV estimates (since addressed), uncertainty about partitioning larval data by stock, and an unexplained and substantial drop in the index during 2004 and 2005, years with anomalously cold bottom temperatures (EcoAp 2009). Understanding the drivers of spawning distribution will contribute to the interpretation of the larval index, which in turn will contribute to evaluating the trawl survey trends in the abundance of spawning age silver hake. The trawl survey index has also been questioned during the assessments due to uncertainty over whether distribution shifts have altered the catchability of large silver hake. By understanding the drivers of adult and juvenile distribution on the trawl survey we will be able to quantify shifts in habitat specific to each life stage over the duration of the trawl survey time series.

DELIVERABLES

- An analysis partitioning the effects of age-truncation and shelf-warming on the distribution of silver hake. This analysis will be coded in R and will be documented to allow it to be applied to other species with age-structured data.
- An evaluation of whether the distribution of spawning and juvenile settlement has changed in a manner coherent other observed changes in distribution.
- Larval tracking code for stock ID methodology will be made available to NMFS researchers.

RESULTS FROM PRIOR FUNDING

*Hare, Overholtz, Able (**Richardson post-doc**), Developing zooplankton and larval indices for use in Atlantic herring (Clupea harengus) stock assessments FY07-FY08* **–** A larval index was developed and contributed to the update Atlantic herring stock assessment (Richardson et al. 2010). A manuscript and presentation at the 2012 assessment detailed the affect of haddock predation on herring eggs on the herring larval index and herring population trends (Richardson et al. 2011).

Churchill, *Runge, Predictors for Larval Transport Success and Recruitment for Cod in the Gulf of Maine FY08-FY09* - A wind index for recruitment success of age-1 cod to the Gulf of Maine stock was developed and supplied to the Population Dynamics group at the NEFSC. A larval tracking model was also developed (Churchill et al. 2011, Runge et al, 2010).

Richardson, *Hare, Jacobsen, Legault, Mountain, Nye, (**O'Connor post-doc**) The Mid-Atlantic cold pool and stock assessments: developing environmental indices at the range limit of species FY10-FY11.* Two distinct methodologies have been developed to test for changes in the cold pool characteristics through time. The cold pool index was presented at the 2012 Yellowtail flounder assessment as an index that could account for the recent decline in yellowtail recruitment.

*Hare, **Churchill, Richardson**, Jech, Deroba, Walsh-Improving fishery-independent acoustic and larval indices for use in the upcoming benchmark Atlantic herring assessment FY 11.* A initial methodology was developed (and is currently being revised) to determine herring spawning locations using particle tracking models and sampled larval data. We used this methodology to evaluate the hypothesis in the 2009 assessment that the spawning distribution and timing of herring had changed, and thus the acoustic index of herring was not valid. The results were presented at the 2012 herring assessment and it was agreed that the prior rationale for excluding the acoustic herring index from the assessment model was not valid.

REFERENCES

Almeida FP. 1987. Stock definition of silver hake in the New England-Middle Atlantic Area. North American Journal of Fisheries Management **7**, 169-186.

Benson AJ, McFarlane GA, Allen SE, Dower JF. 2002. Changes in Pacific hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift. Canadian Journal of Fisheries and Aquatic Sciences. 59: 1969-1979.

Bolles KL, Begg GA. 2000. Distinction between silver hake (*Merluccius bilinearis*) stocks in U.S. waters of the northwest Atlantic based on whole otolith morphometrics. Fishery Bulletin. **98**: 451-462.

Churchill, JH, Runge J, Chen C. 2011, Processes controlling retention of spring-spawned Atlantic cod (*Gadus morhua*) in the western Gulf of Maine and their relationship to an index of recruitment success. *Fisheries Oceanography*, 20, 32-46

Dorn MW. 1995. The effects of age-composition and oceanographic conditions on the annual migration of Pacific whiting, *Merluccius productus*. CalCOFI Report. 36: 97-105.

Ecosystem Assessment Program. 2009. Ecosystem Assessment Report for the Northeast U.S. Continental Shelf Large Marine Ecosystem. US Department of Commerce Northeast Fisheries Science Center Reference Document. 09-11; 34 p

Friedland KD, Hare JA. 2007. Long-term trends and regime shifts in sea surface temperature on the continental shelf of the northeast United States. Continental Shelf Research. 27: 2313-2328.

Hsieh CH, Reiss CS, Hewitt RP, Sugihara G. 2008. Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. Canadian Journal of Fisheries and Aquatic Sciences **65**: 947-961.

Jeffrey JA, Taggart CT. 2000. Growth variation and water mass associations of larval silver hake (*Merluccius bilinearis*) on the Scotian Shelf. Canadian Journal of Fisheries and Aquatic Sciences. 57: 1728-1738.

Link JS, Nye JA, Hare JA. 2011. Guidelines for incorporating fish distribution shifts into a stock assessment context. Fish and Fisheries. 12: 461-469.

Northeast Fisheries Science Center. 2011. 51st Northeast Regional Stock Assessment Workshop (51st SAW) Assessment Report. US Dept Commerce, Northeast Fish Science Center Reference Document. 11-02; 856 p

Nye JA, Link JS, Hare JA, Overholtz WJ. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series **393**: 111-129.

Nye JA, Joyce, TM, Kwon Y-O, Link JS. 2011. Silver hake tracks changes in Northwest Atlantic circulation. Nature Communication **2**: 412.

Runge, JA, Kovach A, Churchill J (18 other co-authors), 2010. Understanding Climate Impacts on Recruitment and Spatial Dynamics of Atlantic Cod in the Gulf of Maine: Integration of Observations and Modeling, *Progress in Oceanography*, 87, 251

Woillez M, Poulard J-C, Rivoirard J, Petitgas P, Bez N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (*Merluccius merluccius*) in the Bay of Biscay. ICES Journal of Marine Science, **64**: 537– 550.