Lagrangian based habitat assessment for bluefin tuna (*Thunnus thynnus*) spawning in the Gulf of Mexico

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Inferences of ocean conditions at spawning are biased (distorted) by the time and space disparity between the time of larval collections and the time and place of spawning. During most Southeast Area Monitoring and Assessment Program (SEAMAP) surveys in the Gulf of Mexico (GOM) larvae of Atlantic bluefin tuna (ABFT) are typically 2-10 mm length (3-22 days of age) and have been transported hundreds of km from their source location. Relationships that have been derived between oceanic conditions positive for ABFT larvae correctly classify 58-83% of the sample collections (Muhling *et al.* 2010). The remaining 17-42% is unresolved. Our intent is to reduce this uncertainty by re-examining SEAMAP net collection data of larval size and estimates of age and to use this information to recast the larvae to theoretical spawning source water using ocean model data and Lagrangian backtrack analysis. The end product will be the derivation of a more precise predictive model for ABFT adult spawning preferences, improved spawning habitat maps, and refinement of the ABFT larval assessment of spawning stock biomass. Our goal is outlined in 3 steps: 1) Incorporating dynamic oceanography to determine how larvae arrive at where survey sampling schemes catch them - "How they got there?" 2) Use the drift paths to derive an improved spawning habitat model by comparing the apparent oceanography of where backtrack modeling suggests adult ABFT spawn. 3) Use these drift paths and apparent along path conditions to test emerging hypothesis of larval ecology.

Background:

The Atlantic bluefin tuna (*Thunnus thynnus thynnus*, Linnaeus, 1758) is a large, highly migratory, high value pelagic predator whose spawning range includes the Gulf of Mexico and Mediterranean Sea (Mather *et al*. 1995). The population is managed as two separate spawning stocks (Western - Gulf of Mexico, Eastern - Mediterranean Sea) (Rooker *et al.* 2007) with the western stock designated as a "Species of Concern" (ABTSRT, 2011). Although management entities differ on the status designation of the bluefin tuna, all agree that populations have declined worldwide and up-to-date research is necessary to uphold effective stock rebuilding scenarios (ABTSRT, 2011; Collette *et al,* 2011; COSEWIC, 2011; SCRS, 2010). The western stock primarily spawns in the GOM from April to June (McGowan and Richards, 1989; Scott *et al*, 1993). Tagged adult ABFT migrating to the GOM during the spawning season have been shown to be located in sea surface temperatures of 24-27º C (Block *et al* 2001, Teo *et al* 2007). This range is thought to be within the threshold of optimum survival conditions for larval bluefin tuna, mainly based on ideal metabolic allowances. While temperature preferences for both adult and larval

ABFT has become more widely understood, the effects of dynamics in the upper mixed layer on larval survival remains an integral missing piece on larval survival and recruitment.

Muhling *et al.* (2010) derived a predictive model for ABFT larval habitat in the GOM based on larval collections and oceanographic collections. The assumption was made that larvae of 3-6 days old, but as much as 12 days, were likely to be located in the same water mass in which they were spawned. This was a reasonable assumption given the available oceanographic data. Muhling *et al.* (2010) suggests that their analysis was limited by the coarse spacing of samples and inability to resolve samples to the occurrence of finer-scale oceanographic features. Limited information exists on ABFT spawning locations in the GOM. Our aim is to apply a particle model to NMFS ichthyoplankton survey data and backtrack larvae to a theoretical spawning location while relating them to model estimates of oceanographic conditions.

For many oceanic fish knowledge gaps exist in the recruitment and oceanographic processes affecting early life stages, including those for ABFT (Mariani *et al.* 2010). Lagrangian particle-modeling techniques have recently seen expanded use in addressing many fisheries management problems related to larval dispersal (review in North *et al.* 2009). They are especially useful for problems addressing connectivity between regions for both broadcast spawning invertebrates (Marinone *et al.* 2008 and others) as well as fish (North *et al.* 2009, Johnson *et al.* 2009). Standard methods and protocols are now generally accepted for their application (Grimm *et al.* 2006; Christensen et al. 2007; North *et al.* 2009). Lagrangian particle-modeling has been applied to better understand ABFT spawning in the Mediterranean (Mariani *et al.* 2010), however the hydrodynamic model's time-space resolution (5 day - 14 km) in that study precluded fine scale modeling of individual larvae. As new higher resolution ocean modeling products become widely available the opportunities will arise for innovative Lagrangian modeling applications in fisheries management.

In late spring 2010 the U.S. Naval Oceanographic Office (NAVOCEANO) began distributing the AMerica SEAS (AMSEAS) hydrodynamic model output via collaboration with NOAA/OAR's, Northern Gulf Institute and NOAA/NESDIS. AMSEAS is an oceanographic nowcast/forecast product that covers the entire Gulf Caribbean region at a 3 km, 40 depth implementation of the Navy Coastal Ocean Model (NCOM). Output is distributed for a 3 h, ~2.8 km resolution, 1000 x 1510 grid domain of the Gulf of Mexico and Caribbean (5-32 N and 55-98 W) and includes tidal, geostrophic, and atmospheric driven water motion. Wind forcing (as wind stress), atmospheric pressure, heat, solar, and salinity flux, and surface roughness within AMSEAS are derived from the Navy regional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®; Hodur *et al.*, 1997; Chen *et al.* 2003). Because of its wide Gulf-Caribbean coverage and moderate resolution (3 km x 3 h), AMSEAS is ideal for addressing larval fish studies in the GOM.

Preliminary backtracking of SEAMAP, ABFT larval catches from spring 2011 demonstrates some of the capabilities of combining AMSEAS data with Lagrangian backtrack models for ABFT larvae. Fig. 1 shows an example backtrack of one station

positive for ABFT. First, the distance a larva travels from the egg to larval stage is of 120 to 160 NM. Second, the time component, of 3 to 16 days (this example), results in major changes in the oceanographic scene. Finally, along track spread is variable, depending on oceanographic conditions, whether larvae transit through regions of upwelling (divergence) or downwelling (convergence). Many larvae have drifted hundreds of km from their source, days before the survey ship has left the pier.

Available ocean model data and Lagrangian back-track capabilities in combination with several years of ABFT larval samples provides a unique opportunity for NOAA Fisheries to improve the understanding of ABFT spawning in the GOM as well as the precision of the indices of spawning stock biomass.

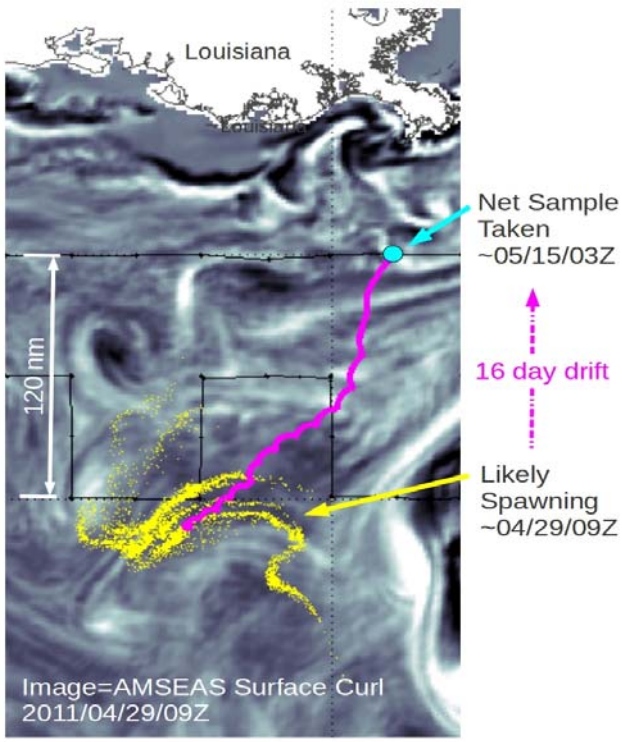

Figure 1. Example of the time-space disparity of where larvae are caught in a net, versus where they likely originated. Yellow - probable spawning, for an ensemble run of n=5000 particles in the upper 25 m, Pink - mean drift track, light blue - where larvae were caught. Example was calculated from preliminary analysis and modeling from the 2011 SEAMAP survey and AMSEAS ocean model output.

Approach:

This FATE project is a demonstration using existing and forthcoming data that will initially examine three years of ABFT larvae from SEAMAP samples (2011, 2012, and pending 2013) that have co-occurring AMSEAS data (operational after May 2010). The approach will occur in 3 steps as follows:

1) Backtrack Modeling: using an oceanographic model output to derive apparent larval drift paths from likely spawning source to net capture.

2) Indice Improvement: Spawning habitat models will be tested for improvement by using the apparent oceanography of where backtrack modeling suggests adult ABFT spawned versus where modeling suggests they did not spawn to formulate a new model. This new

model will be compared to the old model which was based on conditions at location of capture.

3) Emerging Biology: Drift paths and apparent along path conditions will be used to test emerging hypothesis of vertical migration, predation, and natural mortality on the larvae.

Step 1) Use the time and place of all net tows, both Positive for ABFT larvae (+BFT) and those Negative (-BFT) to re-cast net samples of larvae back in time to an apparent spawning site. Fish lengths and inferred age are only available for the +BFT SEAMAP stations and not for the -BFT stations (nonexistent fish). To provide an ability to model all the potential larvae, we will derive an overall fish size-probability distribution of each survey's catch of larvae and use these distributions in generating matching sets of +BFT and -BFT backtracks as well as the larvae-specific backtracks, i.e. time-age and location of those actually caught. Backtracking is a reverse process, using the hydrodynamic model data sequence and current velocities in reverse (-1 * U and V) to obtain reciprocal tracks to source (Nero *et al.* 2012). Comparison of the overall +BFT backtracks to the larvae specific backtracks will provide a measure of suitability of using the overall distributions. Several backtracking schemes will be evaluated in Step 1 and will include increasing levels of biological realism - (a) Growth, (b) passive vs. active diel migration, and (c) modifications with age. We will evaluate test ensembles of n=100, 1,000, 10,000 to determine best computational cost-benefits with mean track end point comparisons, time subdivision steps of 3h, 5, 10, 100 evaluations, and dispersion schemes being pure random walks or those based on shear.

Step 2) Construct multivariate probability distributions of oceanic conditions for the +BFT and -BFT and use discriminant function analysis or classification tree (Muhling *et al.* 2010) to construct a classification algorithm suitable for classifying hourly slices of AMSEAS data as either +BFT or -BFT water. We will then apply the classification routine to the 3h AMSEAS data, estimates of actual +BFT in relation to total potential +BFT sample volume in order to rescale the larval catch index (Ingram et al. 2010). Our proof of concept will be a comparative analysis of the indices derived from the established Muhling *et al.* (2010) indice versus the new indice proposed herein. Additionally, Step 2 may provide valuable insight into the conditions at spawning as the atmospheric parameters in AMSEAS (solar, heat, & salinity flux, daytime heating & rainfall) measure cloud cover and combined with surface roughness, wind stress, etc, we will be able to estimate sea state, night time illumination (with full moon -new moon) and provide new insight into sea conditions at spawning including separate data available for ocean color (FSU collaboration).

Step 3) Test the hypothesis concerning the biology of larval BFT. The apparent along-path conditions to test emerging hypothesis of larval growth and mortality. We hypothesize that more larvae and potential prey would be advected together in convergent flow fields than in divergent flow fields and that convergent fields may provide higher survivorship and recruitment. Because of AMSEAS high time-space resolution, backtrack trajectory patterns can be used to infer a larvae's ocean experience and if that experience included a convergent environment favorable for high encounter rates with prey organisms or a

divergent environment that would be less favorable. If cannibalism plays a major role in ABFT larval development (Nishimura and Hoshino 1999), then high survivorship and healthier stronger larvae should be expected in SEAMAP samples taken downstream of the convergent flow fields (more larvae advected together increasing their feeding opportunities). In a neutral flow field backtrack trajectories will reflect the base random "kick" programmed into the model. This base kick becomes more spread on backtracking upstream into a *Convergent* flow and more concentrated on backtracking upstream into a *Divergent* flow. We propose to examine an index of along track convergence/divergence as one important parameter in this study. Although not the primary purpose of this study, this concept of classifying larval trajectories if fruitful will form the basis of subsequent proposals.

Benefits:

The current approach in calculating annual larval abundance for the western stock is a zero-inflated delta lognormal index, as described in Ingram *et al* (2010). This approach has yet to incorporate the local environmental conditions at each sampling station as potential descriptors of the overall abundance distribution. We will derive quantitative differences from theoretical spawning site vs. actual sampling site as potential inhibitors of the ZIDL index. Furthermore, including the along-path ecological parameters to our modeling approach will provide a more precise initial abundance estimation as derived from the survey data. To achieve this goal we will assist in developing an abundance index that will be more representative of the local conditions experienced by the annual spawning stock biomass, as well as compare the significance to the current larval index. This model will also bring the capability to test these assumptions, and in turn reduce variability that exists in current GOM larval indices. Creating a generalized model will also offer parameterization capabilities for other native GOM pelagic species, which include Yellowfin Tuna (*Thunnus albacares*), Blackfin Tuna (*Thunnus atlanticus*) and Skipjack Tuna (*Katsuwonus pelamis*). Our aim is to share research at annual bluefin tuna Workshops among NMFS researchers and collaborators and also internationally at ICCAT bi-annual bluefin tuna stock assessments.

Deliverables:

- A research report documenting the backtrack modeling results for the GOM, showing the spatiotemporal distribution of larvae caught at sea, their hypothesized dispersal from spawning locations and apparent adult ABFT spawning preferences based on ocean models.
- A journal article documenting a comparative analysis of the larval backtrack-enhanced habitat model with the Muhling *et al* (2010) larval habitat model.
- Distribution of scripts (MATLAB and open source Octave) for other NMFS science centers interested in using backtrack analysis of sampled larvae based on operational NOAA ocean model products.

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Budget: