Exploring the utility of nonlinear time series models forecasting stock abundance of red snapper \textit{(Lutjanus campechanus)} in the Gulf of Mexico

Hui Liu\textsuperscript{1}, Mandy Karnauskas\textsuperscript{2}, Xinsheng Zhang\textsuperscript{3}, Brian Linton\textsuperscript{2}, Clay Porch\textsuperscript{2}

\textsuperscript{1}Department of Marine Biology, Texas A&M University, Galveston, TX
\textsuperscript{2}NOAA/NMFS, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, FL
\textsuperscript{3}NOAA/NMFS, Southeast Fisheries Science Center, 3500 Delwood Beach Rd, Panama City, FL

Project Summary:

Fisheries stock assessment methods generally rely on appropriate assumptions of model structures, process errors and observation errors. Stock assessment models incorporate varying levels of mechanistic detail in specifying the key elements of population structure and function. In many instances, the choice of model structure and complexity reflects a tradeoff between realism and accuracy, due to the potential for increased uncertainty in parameter estimation in more complex models (Yodzis 1998). Uncertainty in specifying the critical structural elements to be included in stock assessment models, however, remains a dominant source of risk and uncertainty for fisheries management. These uncertainties and assumptions tend to limit our ability to conduct sustainable management of marine living resources.

An alternative and complementary approach to avoid such uncertainties is to use a class of phenomenological models fit to time series data using nonparametric methods, without the requirement of specifying a particular model structure. Here, we propose to explore the utility of such a flexible class of nonlinear time series models (Sugihara & May 1990, Sugihara 1994) to circumvent the complexity of conventional stock assessment models and develop short-term forecasts of the stock abundance for fish populations. Application of these nonparametric models enables us to get around the dilemma of specifying a particular model form, while allowing considerable flexibility in representing the nonlinear ecological processes in the ocean. These simpler models presumably can outperform more complicated mechanistic models in short-term forecast skill. This general approach has been successfully applied to marine systems (Dixon et al. 1999, Hsieh et al. 2005, Anderson et al. 2008), and recently to marine fish populations (Glaser et al. 2011, Liu et al. in press). We note that nonlinear forecasting methods are currently of limited use in marine fisheries and particularly from a management perspective, as they only have been applied to produce short-term predictions and may only be useful for short-term projections in stock trends. However, the methods are highly valuable in that they are able to quantify the complex, nonlinear behaviors that are recently recognized in marine fisheries dynamics driven by internal and external forcing (Glaser et al. 2011, Liu et al. in press). Therefore, nonlinear forecast models provide us another perspective of thinking about the assumptions and uncertainties of classical assessment models. In this respect, projecting stock abundance from a nonlinear perspective may serve as useful complements to stock assessments based on stable dynamics.

Project Background:

Red snapper \textit{(Lutjanus campechanus)} is among the most ecologically and economically important fishes in the northern Gulf of Mexico (GOM) (Patterson et al., 2007), and has been fished in the GOM since 1850 (Camber 1955). Fisheries of the GOM red snapper (hereafter Gulf red snapper) are considered to be one of the most controversial in the U.S., as they
collapsed in the late 1980s when stock biomass became too low to be fished commercially (Cowan et al. 2010). Recent studies suggest that the Gulf red snapper population is composed of two stocks, separated by the east and west of the delta of the Mississippi river (Cowan et al. 2010), and the recent stock assessments have been carried out separately. The GOM Fisheries Management Council currently is considering whether Gulf red snapper should be managed as a single Gulf wide stock or as separate eastern and western stocks, but scientific information on which to base this decision are lacking.

Gulf red snapper has been assessed to be overfished and undergoing overfishing since at least the late 1980s. Fisheries management of Gulf red snapper began in 1989; however, management is complicated because the greatest source of mortality is believed to come from shrimp trawl bycatch rather than from directed harvest (Cowan et al. 2010). Assessment results indicate that reduction of bycatch mortality on juveniles was a key to stock recovery. Moreover, the last benchmark assessment for Gulf red snapper illustrates that recruitment and stock productivity may have increased since the late 1980s (Cowan et al. 2010). Despite all efforts to solve the bycatch problem and recover Gulf red snapper, the stock remains significantly overfished (Porch 2004), and only recently has the stock started to show signs of recovery (Cowan et al. 2010). This discrepancy indicates that the currently used stock assessment models may not sufficiently describe the important dynamics affecting Gulf red snapper.

Two assessment models have been applied to evaluate the stock status of Gulf red snapper: age-structured assessment program ASAP (Legault & Restrepo 1998) and age-structured assessment model CATCHEM (Porch 2005). The ASAP model was used in the 1999 assessment of Gulf red snapper, however, the model tends to fail to converge when the extended data series was applied to ASAP. In contrast, the projected stock status tends to be constant between short and long time-series runs from CATCHEM, and this model was therefore selected for the 2005 assessment of Gulf red snapper. Deterministic projections for future stock abundance based on the Beverton-Holt recruit model were made with assumptions that the recent time-series of high recruitments would not continue; however, this assumption represents a significant source of uncertainty. As a result, the review panel indicated that only short-term projections should be considered, with the different $R_0$ settings providing a suitable bound on recruitment uncertainty.

The high steepness of the stock-recruitment relationship would suggest that factors besides spawning stock biomass are strongly influencing recruitment. One possibility is that external sources are supplying recruitment; however, recent modeling work has indicated that recruitment from the southern Gulf of Mexico is sporadic and extremely low (Johnson et al., in review). A second possibility is that environmental forces affect recruitment, and while these forces are important to consider, the dangers of incorrectly incorporating recruitment-environment relationships into stock assessments are well-recognized (Haltuch & Punt 2011). A key strength of the nonlinear time series approach to stock assessment is that environmental variables are not directly incorporated into the forecasts – rather, the important environmental forces are thought to be implicitly expressed via the behavior of the time series data. Thus, this approach allows us to incorporate environmental dynamics into the stock assessment process despite our ignorance about the mechanistic relationships between stocks and their environment.

The overarching goal of this proposal is to explore the utility of nonlinear time series models for forecasting stock abundance of fish populations in the Gulf of Mexico with a focus on the Gulf red snapper, one of the most data-rich species in this region.
The specific objectives are as follows:

1. Conduct nonlinear time series analysis on catch, size, and age composition data for East and West Gulf red snapper, to understand whether East and West stocks are dynamically coherent (i.e., whether they share similar dynamics or respond to the same environmental forcing). These results will provide useful products for the Management Council to inform whether stocks should be managed together or as two separate populations.

2. Compare forecasts produced from nonlinear models and the conventional stock assessment methods. These results will provide insight as to whether the conventional stock assessment methods are sufficiently capturing important environmental dynamics affecting the stock.

3. Apply the concept of co-prediction analysis to increase forecast skill associated with relatively short time series data, and to examine possible associations between the stock trends of Gulf red snapper and other relevant species and environmental variables. These analyses will elucidate relationships between the study species and other components of the ecosystem. Components found to be dynamically related to the species can be recommended for incorporation within traditional stock assessments.

This project addresses the FATE RFP objectives: “improve stock assessments or fisheries management through the inclusion of environmental or oceanographic information.”

Project Approaches:

Nonlinear forecasts

The nonlinear modeling approach we use is nonparametric in the sense that there is no specified functional form. Rather, our approach involves interpreting the time series as having been produced from dynamics that reflect motion on an attractor.

Fig. 1 An illustration for reconstruction of a 3D phase space and attractor (dark grey geometry in the right panel) using the time-lagged coordinates embedding technique (Takens 1981) in the middle panel. (Liu et al. in review)

We reconstruct the attractor (and the coordinate space it occupies) by plotting lagged coordinates of the time series (Fig.1). According to Taken’s Theorem, when the subsequent time lags are plotted on different coordinates, they act as proxies to reconstruct the true, unknown attractor (Takens 1981). Although the true dimensionality of the system is unknown and potentially very high, it can be shown that an understanding of the number of key dimensions affecting the variable(s) of interest can be determined from the histories recorded in the time series. In practice, the effective dimensionality required of the system to achieve significant predictability is often relatively low (Sugihara & May 1990, Sugihara 1994), thus facilitating the use of relatively short time series in the analysis. Forecasts are performed via a nearest-neighbor
algorithm which tracks the behavior of the data through multi-dimensional space (i.e., future behavior is predicted based on patterns in past behavior of a similar nature).

**Analytical approach**

To test for evidence of complex nonlinear dynamics of Gulf red snapper, we will conduct univariate nonlinear analysis by applying the simplex projection model (Sugihara & May 1990) to identify the dimensionality of the (unobserved) underlying ecological system based on past values of a restricted number of measured variables. We will then use the S-map model (Sugihara 1994) to estimate the presence of nonlinearity in the time series, and then forecast the projection of the dynamics of fish stock. The S-map technique involves using out-of-sample forecast skill as the determinant of the ‘best’ model. For the case of a single time series, the general approach involves splitting the series and building the model using one portion of the data (referred to as the library set) while reserving the withheld portion to test the model (the prediction set). These methods are used to estimate the ideal number of dimensions with which to describe the behavior of the time series, and classify nonlinearity in the individual time series (Glaser et al. 2011, Liu et al. in press). If East and West populations of Gulf red snapper are estimated to have different dimensionalities, for example, this will support the hypothesis that the stocks are separate and should be managed as such.

The above statistical techniques will be applied to age-structured survey data and commercial catch data available for Gulf red snapper (Table 1). Short-term nonlinear projection of age-structured abundance trends will be conducted to make one-year, two year and three year-ahead predictions. Meanwhile, deterministic projections of the future stock abundance from the traditional age-structured models CATCHM and Stock Synthesis will be available from the current red snapper assessment process. Both the nonlinear analyses and the stock assessment models will be run for the entire Gulf red snapper population, and separately for East and West stocks. Prediction skill will be quantified based on differences between observed indices and predicted indices from each method.

**Table 1. Commercial and recreational fishery data available for Gulf red snapper**

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Commercial</th>
<th>Recreational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size Composition</td>
<td>1984-2011</td>
<td>1984-2011</td>
</tr>
</tbody>
</table>

We will apply the concept of co-predictability to increase the forecast skill associated with relatively short time series data, and to examine possible associations between the stock trends of Gulf red snapper and other relevant species and environmental variables. For nonlinear systems, correlations between system components may be weak or undetectable even if they are dynamically coupled because parametric correlation analysis will only detect linear associations. Co-predictability provides an alternative quantitative measure of model forecast skill and is particularly useful for nonlinear systems (Liu et al. in press). We will carry out co-prediction between Gulf red snapper and other species in the GOM, based on standardized abundance indices. High co-predictability between species indicates significant dynamic similarity. Species to be included in this analysis include other members of the snapper-grouper complex, shrimp, and menhaden.
Co-prediction analysis will also be applied to environmental and oceanographic variables, which are likely influential on the recruitment and population dynamics of Gulf red snapper. We assume inshore and pelagic conditions are important to the dynamics of fish at early ages (age 0 and age 1), whereas offshore environment and forage fishes are related to the dynamics of adult fishes. We will conduct co-prediction analysis including environmental and oceanographic variables (Liu et al. in review), to identify the key processes driving the underlying dynamics of red snapper populations in the Gulf of Mexico. Specifically, the environmental variables (and data sources) to be considered in this analysis include: sea surface temperature (HadISST1), wind strength (North American Regional Reanalysis), various climate indices and geostrophic transport estimates (Atlantic Oceanographic and Meteorological Laboratory), Mississippi River watershed influences (basin precipitation, nitrate concentrations; USGS), and zooplankton biomass (COPEPOD). Several of these variables were previously shown to influence growth rates of red snapper (Black et al., 2011).

Benefits:

This project addresses the FATE RFP objectives: “improve stock assessments or fisheries management through the inclusion of environmental or oceanographic information.” This research will explore techniques for building assessments that incorporate environmental forcing, techniques for projecting stock status under different environmental scenarios, and analyses that quantify uncertainties attributed to model structure, environmental, oceanographic or ecological processes. The benefits of this project are multifold. Firstly, we will provide results to the Management Council which will inform whether or not Gulf red snapper should be managed as a single stock. Secondly, the research will provide insight into whether current red snapper stock assessment models are sufficiently capturing environmental dynamics, and the results can be used to inform improvements to these models. This information will be communicated by the PIs at upcoming red snapper assessment meetings. Thirdly, the approaches in this research will potentially be adoptable to other fish stocks in the GOM and other systems for stock assessment and ecosystem management. Finally, this project will build on the collaborations between academic institutions (i.e. TAMUG) and SEFSC for potential research in the future.

Deliverables:

- Information on the underlying dynamics of gulf red snapper by region and Gulf wide which will be provided to the Management Council to inform whether Gulf red snapper should be managed together or as separate two stocks.
- Short-term forecasts to be provided to SEDAR (Southeast Data, Assessment and Review) to compare with traditional forecasts and inform the performance of the current red snapper stock assessment models.
- A list of species and environmental variables which are found to be dynamically interacting with red snapper populations, which will be candidates for inclusion in future ecosystem-based management and stock assessment activities.
- Dissemination of results through the FATE annual science meeting, other national (Ocean Sciences and the AFS annual meetings) and international (ICES/PICES) conferences as well as in peer-reviewed publications.
References:
Johnson DR, Perry HM, Lyczkowski-Shultz J (in review) Connections between Campeche Bank and Red Snapper populations in the Gulf of Mexico via modeled larval transport.