The role of submesoscale eddies from the Florida Current System on productivity of King Mackerel and other coastal pelagic stocks in the South Atlantic Bight

Principal Investigator:
David Lindo-Atichati

Principal Investigator Institution:
City University of New York, College of Staten Island
2800 Victory Boulevard
Staten Island, New York 10314

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Principal NMFS Investigator Contact Information:
John Walter
Southeast Fisheries Science Center, Sustainable Fisheries Division
John.F.Walter@noaa.gov
305-365-4114
75 Virginia Beach Drive, Miami, FL

Team members:
David Lindo[1], John F. Walter[2]
[1] City University of New York, College of Staten Island, Staten Island, NY 10314, USA
[2] NMFS SEFSC, Sustainable Fisheries Division, 75 Virginia Beach Drive, Miami, FL

PI email and phone:
david.lindo@csi.cuny.edu , +1 786-286-0126

1. BACKGROUND

It has been well-documented that biological productivity in the South Atlantic Bight (SAB) is heavily influenced by meso and sub-meso scale eddies generated by the Gulf Stream (e.g. Lee et al. 1991, Shay et al. 2000; Hyun and He 2010). These eddies spin off of the powerful Gulf Stream, upwelling cool, nutrient rich deep water onto the continental shelf, forming localized productivity 'hotspots' (Fig. 1). While small in size and ephemeral in duration, it is hypothesized that these eddies, might generate as much as 4.3 million metric tons of biological productivity in this region (Lee et al. 1991). It is further well known that the eddy production that fuels this productivity varies annually according to the location and intensity of the Gulf Stream (Fiechter and Mooers, 2003), likely resulting in interannual variation in biological productivity. Yet, to date, the influence of this productivity and its interannual variation has never been explicitly considered in a stock assessment.

In a recent stock assessment for king mackerel (SEDAR 38) there was a clear and strong correlation between recruitment deviations and the longitudinal position of the Gulf Stream offshore of Florida (i.e. Florida Current; Fig 2). The position of the Florida Current serves as a proxy for the intensity or amount of mesoscale eddy production (Fiechter and Mooers, 2003). The significant correlation with recruitment deviations indicates that previously unaccounted for oceanographic process may play a substantial role in population dynamics of king mackerel (KM) and other species in the SAB. As there is an increasing recognition that the productivity of fish stocks is affected by factors beyond stock abundance and fishing pressure (Vert-pre et al. 2013, Szuwalski et al 2014), there is a need to adequately account for these factors in fisheries assessments.

In the proposed research, we will build a new tool for the South Atlantic region which will quantify the mesoscale and submesoscale processes that likely drive dynamics of coastal pelagics, and potentially for other species. The tool is a novel modeling approach, which incorporates a high-resolution hydrodynamic model which is forced by a downscaled atmospheric model at analogous high-resolution (see *Methods)*. The approach was developed by the PI, ground-truthed in other regions based on *in-situ* data, and has been shown to replicate observed ocean dynamics (Lindo-Atichati et al., 2014). The tool will be used to test various hypotheses related to how these eddy processes affect KM stock dynamics, including catch rates, condition and recruitment success. KM is employed as a test species, as preliminary work suggests that stock dynamics are indeed related to smaller-scale physical processes (Fig. 1). However, the tool is general and can be applied to many species or purposes in the SAB region. The proposal responds to FATE Research Priorities # 1, 2, 3, and 6 (see *Benefits*).

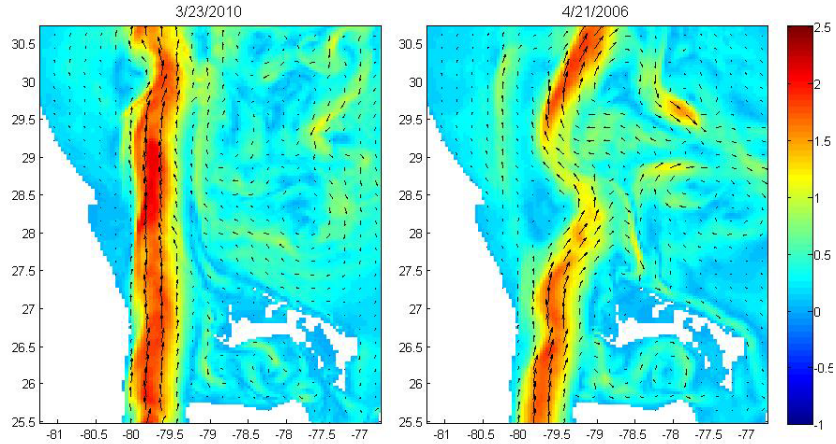

Fig. 1. Translocation of cyclonic eddies from the Florida Current. When the Florida Current is close to shore (left), it impedes development of cyclonic eddies. When it meanders offshore (right), it allows the formation of eddies. Color scale is current velocity in m/s.

2. APPROACH

We propose to develop an oceanographic modeling product that produces a time series of quantitative eddy intensity, and then to test effects of this index within the existing KM, *Scomberomorus cavalla*, stock assessment. The region evaluated is the part of the South Atlantic Bight in the region comprised between the Western boundary of the Florida Current (FC) and the Florida Shelf (FS) and centered at 28°N.

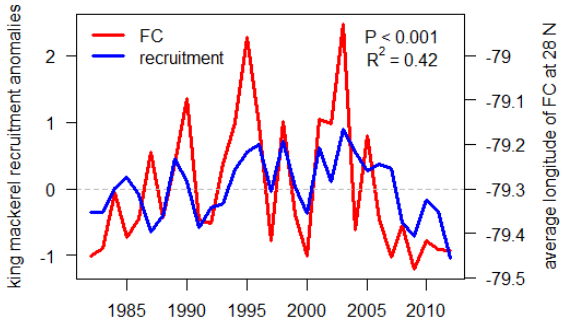

Fig. 2. Correlation between the average longitude of the Florida current and recruitment deviations for the South Atlantic Bight (SEDAR 38).

Preliminary work suggests that the location of the FC, which is presumably linked to the formation of submesoscale upwelling-inducing eddies, correlates with recruitment deviations for KM (Fig.1). Importantly, this is the wintering zone for KM, as well as a number of other coastal pelagic species.

The FC is the southernmost extension of the Gulf Stream, transporting a substantial volume of water (~30 Sv) and close to the East coast of Florida. The FC fluctuates in its East-West orientation, resulting in variation in the mesoscale features that it produces (Rossby et al. 2010). When the FC is offshore, it spins short-duration submesoscale eddies that upwell deep, nutrient rich water, whereas when the FC approaches the shelf, the production of submesoscale eddies is reduced (e.g., Fig. 1).

While preliminary work suggests that FC, and mesoscale eddies proxied by its position may drive KM and other species population dynamics, the mechanistic reasons for this remain unresolved. Recruitment deviations coming from the assessment model can be product of changes in adult or juvenile growth or survival, variation in larval transport or retention, or simply manifestations of other signals in the model such as changes in catchability. Thus we develop hypotheses, outlined below in *Hypothesis testing*, on a continuum of inference as to if, and ultimately how, these oceanographic features might affect KM stocks.

Methods

<u>Submesoscale Features and the Hydrodynamic Model.</u> Submesoscale features arise through nonlinear instabilities of mesoscale currents, at horizontal scale of O(1– 10) km, *i.e.*, less than the first baroclinic deformation radius; a vertical scale of O(100) m, *i.e.*, thinner than the main thermocline; and a time scale of O(1) day. Capturing the full strength of submesoscale vertical movements requires horizontal model resolution of the order of one tenth of the internal Rossby radius of deformation. This would require a resolution of O(1) km in the east Florida Shelf. Therefore, we will downscale the operational Hybrid Coordinate Ocean Model (HyCOM; www.hycom.org) at a resolution of 1/100° (*ca.* 900 m) horizontally with 26 vertical layers within a 100 km x 100 km domain (27.5-28.5°N, 80.6-79.6°W). This model domain encompasses shallow waters of the Bethel Shoal on the Florida Shelf (FS). The model will calculate hindcasts of 3-D ocean fields (flow components u, v, w, temperature and salinity). To achieve more realistic simulations, we will force the ocean model with the Weather Research and Forecasting atmospheric model (currently 27 km resolution) at 1/25° (*ca.* 4 km) horizontal resolution. The lateral boundary conditions will be provided by the coarser resolution (1/12°) global data-assimilated HyCOM model. The modeling effort will be

achieved at limited computational cost on a the high-performance computing center of the City University of New York. Ocean data assimilation will be established as an option in the model. Model validation of water movement will be delivered by drifters, which are released as part of a separate study. The hydrodynamic models will provide estimates of 3-D currents, which move virtual larvae (see *Biophysical Model)* below, and temperature and density, which affect larval buoyancy and larval mortality (Vikebo et al. 2007).

An existing complementary effort has been carried out by Kourafalou and Kang (2012). This is a high-res 900 m resolution model that covers the Southwest Florida Shelf, the Southeast Florida Shelf, the Atlantic Florida Keys Shelf and the Straits of Florida. The northern boundary of this model domain is at the edge of this target study region. The model proposed in the present research will be nested with FKeyS-HyCOM and will complement the effort of understanding the circulation processes and larval exchanges along this critical region.

Model groundtruthing. The short time and space scales of submesoscale features coupled with the need to develop a time series dating back many years necessitate a model-based approach. As with any modeling it is critical to evaluate model performance against empirical data. To groundtruth the hydrodynamic model predictions we will use data from satellite tracked surface drifters deployed in a separate study in the region. The drifters are part of the Global Drifter Program (GDP), a component of NOAA's Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). Drifters provide near-real time surface velocity and sea surface temperature, and allow quantification of submesoscale-driven relative dispersion (Lumpkin and Elipot, 2010) which will then be compared against model predictions.

Biophysical Model. For hypotheses relating to the recruitment dynamics of KM, the hydrodynamic model described above will be coupled with a complex biophysical model, the Connectivity Modeling System (CMS; Paris et al. 2013). The CMS is a probabilistic, multi-scale biophysical model: probabilistic because individual particle attributes are drawn at random from biologically realistic trait distributions; multi-scale since it moves particles using a nested-grid framework that is independent of the ocean models, i.e., capable of using multiple ocean models in the same application. The CMS has a stochastic Lagrangian framework, where particles take a random step driven by the local turbulence (Okubo 1971, Paris et al. 2004; North et al. 2008). The CMS generates larval trajectories and connectivity estimates by coupling a series of stand-alone modules. Essential modules for this study include a habitat module representing spawning and settlement nodes of the connectivity matrix.

To test hypotheses regarding FC dynamics, we will calculate a number of indicators of the current dynamics. These are as follows:

1. **Location of the Florida Current front**. The location of the FC front will be determined from the region of maximum horizontal gradient of satellite derived sea surface height (SSH). Specifically, the westernmost locations of the FC is detected from the maximum longitude of the SSH contours corresponding to the location of the maximum gradient of SSH. This algorithm has recently been used to provide the most comprehensive analysis of the long-term variability and effects on larval distribution of the Gulf of Mexico Loop Current and Rings (Lindo-Atichati et al., 2012, 2013).

2. **Okubo-Weiss methodology for eddy detection and quantification.** Potential eddies will be identified by applying the Okubo–Weiss parameter (W), which allows separating vorticity-dominated regions (Isern-Fontanet et al. 2004). The Okubo–Weiss parameter has been widely used to detect eddies in the ocean (e.g. Font et al. 2004; Isern-

Fontanet et al. 2006; Chelton et al. 2007; Chaigneau et al. 2008) and recently to understand mesoscale structure of larval fish assemblages (Morales et al. 2010). This parameter is defined as

$$W = s_n^2 + s_s^2 - \omega^2 \quad (1)$$

$$s_n = \mathrm{d}u/\mathrm{d}x - \mathrm{d}v/\mathrm{d}y \quad (2)$$

$$s_s = \mathrm{d}u/\mathrm{d}y + \mathrm{d}v/\mathrm{d}x \quad (3)$$

where s_n and s_s are the normal and shear components of strain, ω is the relative vorticity, and u and v the horizontal components of geostrophic velocity fields. Cyclonic and anticyclonic eddies are distinguished by the vorticity sign ($-$ or $+$) in their centers. With this method we will develop nine Eddy Indices: 1) eddy number, 2) detection time 3) relative and potential vorticity, 4) center, 5) radius, 6) sea height anomaly, 7) eddy kinetic energy, 8) propagation speed, and 9) duration of identified submesoscale eddies.

Hypothesis testing framework:

Our hypothesis testing framework will rely upon a combination of testing the significance of the indices of eddy intensity within the integrated modeling framework (Stock Synthesis). The index can be linked to several different components; recruitment, growth, mortality or catchability that each may reflect the underlying process by which eddies may influence mackerel population dynamics. Information theoretic criteria can be used as the same number of data (same index) can be correlated with each specific process allowing for an exploration of the underlying mechanistic process. The second part of the hypothesis testing will involve evaluating external empirical data related to prey abundance or mackerel condition factor. Hypotheses to be tested are as follows:

H1: The presence of submesoscale eddies is related to increased catch rates of king mackerel. KM are known to aggregate to mesoscale oceanographic features (Wall et al 2009). Hence it is possible that these features simply aggregate KM and lead to changes in catchability giving a false signal to the assessment model and not necessarily a signal of increasing abundance. This is the first hypothesis that must be tested as to whether including the index of eddy intensity correlates with catch per unit effort deviations. Analysis will also be carried out on landings data on a broader scale, e.g., considering whether statistical areas and times of high eddy activity are correlated with increased landings.

H2: The presence of submesoscale eddies is related to increased condition of adult king mackerel during in the wintering zone. Submesoscale eddies may create hotspots for prey and hence increase feeding success for adult KM which could increase growth, fecundity or survival, which would all manifest within the SEDAR 38 assessment model as recruitment deviations. Eddy detection metrics will be correlated with length at age data or length-weight data, on a monthly or seasonal and statistical area basis. The expectation is that when and where more vigorous eddy fields are present, feeding success is greater and condition or growth is higher. Within the stock assessment model, the index of eddy intensity can be tested as to whether it predicts changes in growth rate, which would be expected with a change in fish condition.

H3: The intensity of submesoscale eddies is related to increased prey abundance of juvenile KM recruits. Eddy detection metrics will be correlated with abundance of important bait species, such as thread herring, Spanish sardine, scaled sardine, and anchovies, on a monthly or seasonal and statistical area basis. These data are available in the SEAMAP South Atlantic Coastal Survey, which began in 1986.The expectation is that when and where more vigorous eddy fields are present, baitfish will occur at higher densities.

H4: The dynamics of the FC are linked to recruitment success of king

mackerel. The hydrodynamic model will be coupled to the biophysical model, and the process of recruitment will be simulated, using similar methods as those carried out for other species (Karnauskas et al. 2013). Particle releases, representing eggs/larvae, will be carried out from estimated spawning areas during the summer spawning season. Realistic larval behaviors, such as vertical migration, will be parameterized based on information from MOCNESS tows. The number of larvae remaining in the South Atlantic after 30 days – the time at which scombrids typically gain good swimming ability – will be calculated for each year, and an annual recruitment strength index will be developed. This index will be compared to recruitment deviations from the KM stock assessment model.

Each hypothesis addresses a separate mechanism by which the environment may affect the dynamics of the study species: H1- influencing catch rates reflects that these features may simply alter catchability and have a nuisance impact upon the assessment; H2 reflects that these eddies may improve adult fish condition; H3 reflects that these eddies my increase prey for juvenile KM increasing juvenile growth and survival; and H4 reflects that recruitment may be linked to oceanographic transport or retention processes.

3. BENEFITS

This research addresses the following FATE Research Priorities: (#1) - testing hypotheses to investigate specific mechanisms driving interactions between fisheries and environmental drivers, (#2) - developing spatio-temporal models that investigate the effects of environmental variability on distributions, growth, recruitment, migration, and larval dispersal, (#3) - developing indicators that could be used in ecosystem-based fisheries management, and (#6) - evaluating the utility of incorporating oceanographic indices into stock assessment models. Specifically, this project will be the first to directly incorporate a metric related to one of the key determinants of productivity in the South Atlantic Bight into a stock assessment for a valuable species. It will elucidate the mechanistic process by which oceanography affects production of a key fishery species, facilitating improved assessment and ultimately better management of KM and related species. Furthermore, the results derived from this project will be applicable other species within the South Atlantic Bight, and to ecosystem-level research.

4. DELIVERABLES

End Year 1:

- Hydrodynamic model for the Florida Shelf for from 1992 to 2014
- A peer-reviewed publication on model parameterization with drifters, submitted
- A peer-reviewed publication on hypotheses in regards to king mackerel, in preparation
- Presentation at appropriate conferences, including FATE meetings

End Year 2:

- A peer-reviewed publication on hypotheses in regards to king mackerel, submitted
- Presentations at appropriate conferences, including FATE meetings
- Communication with South Atlantic Fishery Management Council and other management audiences

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