Cooperative development of dynamic habitat models informed by the Integrated Ocean Observing System (IOOS) informs fisheries management decision making in the coastal ocean.

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***Abstract-* Defining pelagic habitat indicators for migratory fish is particularly interesting and challenging due to the complex interaction between the marine food web and the physical variability. Through a multidisciplinary study, a group of experts in marine ecology, physical oceanography and stock assessment from the fishing industry, government and academia developed a method to explicitly account for shifting habitat distributions in fish population assessments. The study group initially developed a thermal niche model for an important short-lived pelagic forage fish, Atlantic Butterfish (*Peprilus traicanthus*) in the Northwest Atlantic Ocean. This niche model was coupled to a hindcast of daily bottom water temperature derived from a de-biased regional numerical ocean model (ROMS) in order to project thermal habitat suitability in the Northwest Atlantic on a daily basis over the last 40 years. The hindcast of thermal habitat suitability was used to estimate the proportion of thermal habitat suitability available on the Northeast US continental shelf that was sampled on fishery-independent surveys conducted during the spring and fall. We were able to create 40 years of daily maps of predicted butterfish thermal habitat suitability. This time series of Habitat Suitability was then used to determine a time dependent availability, or stock range, based on butterfish thermal niche space. The time dependent availability was then provided to the stock assessment scientists for inclusion in the model.**

Index Terms—Habitat Models, Ocean Observing, Fisheries.

I. Introduction

Defining pelagic habitat indicators for migratory fish is particularly interesting and challenging due to the complex interaction between the marine food web and the physical variability. The rapid evolution of the Integrated Ocean Observation System (IOOS), made possible through interdisciplinary partnerships and networked data sharing, provides descriptions of coastal ocean hydrography and hydrodynamics at fine scales of space and time and regional spatial extents. This allows hydrography and hydrodynamics to be the foundation of a seascape ecology in the way that geography and geophysics appropriately serve as the foundation of terrestrial landscape ecology.

Our purpose was to develop a time varying estimate of availability of the Atlantic butterfish stock to fishery surveys to be considered in the population assessment model. Availability was defined as the proportion of the stock falling within the space-time frame of a fishery independent survey. The primary reasons for focusing on availability were, 1) the assessment is largely driven by fishery independent surveys because fishery landings and discards have been low since 2000 and, 2) recent changes in ocean

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temperatures may have caused shifts in species range and migration dynamics that may be systematically affecting the availability of the stock to surveys. We assumed that catchability (Q) is the product of availability (ρ) and detectability (δ), where availability (ρ) is as defined above, and detectability δ is the proportion of fish within the footprint of an average trawl tow captured in the net. We assumed availability can be estimated as the proportion of the stock's habitat area falling within the space-time frame of a fishery independent survey by combining information about environmental heterogeneity controlling species range and migration dynamics at a broad, regional extent with locations and times of survey samples.

II. Background

A. Ocean Observations:

Since 1992 the Rutgers University Center for Ocean Observing Leadership (RUCOOL) has developed and maintained a coastal observing system in the Mid Atlantic Bight (MAB). This effort has focused on sustained technologies that deliver observations and products across the shelf. In October of 2007, this sub-regional effort joined with other efforts in the MAB to develop a fully regional scale observing presence called the Mid Atlantic Regional Association Coastal Ocean Observing System (MARACOOS). MARACOOS is funded through the NOAA Integrated Ocean Observing System (IOOS) program. By partnering with RUCOOL, the MARACOOS data footprint covers a large part of the Northeast U.S. Continental Shelf Large Marine Ecosystem (LME) in which climate and fisheries are the primary driving forces [1]. This observatory is designed to support fisheries ecosystem management decisions in this LME. MARACOOS brings three key technologies that allow for fine scale characterization of the coastal ocean including the acquisition of data streams from U.S. and foreign satellites in space, a network of high-frequency radars deployed along the shore, and a fleet of robotic gliders flying beneath the ocean surface.

These technologies sample at the broad spatial and fine temporal scales required to describe the pelagic environment that affects fish distributions in coastal marine ecosystems. The dynamics of pelagic factors likely produce shifts in the locations, timing of formation and durations of optimal habitats. An assessment of how well pelagic water mass variation measured by ocean observatories explains variation in the abundance of marine resource species is particularly vital given growing concern about the effects of changing climate on marine ecosystems. If observatory data streams and the associated data assimilative numerical models can be used to identify habitats fish use, then the ecological habitat indicators derived can be mapped dynamically using observatory nowcasts/forecasts to be used in spatial fisheries management.

B. Community development:

This research was conducted through a collaborative group of fishing industry members, academia, federal fisheries managers, and government fisheries scientists. The industry participation from multiple sectors and ports in the MAB contributed their knowledge of both the specific fishery and the ecosystem itself. The academic expertise consisted of a social scientist, physical and biological oceanographers, and fisheries and outreach scientists. Federal participation included expertise in fisheries habitat/ecology, population dynamics, and management from the NOAA/NMFS, the Mid Atlantic Fisheries Management Council, and the

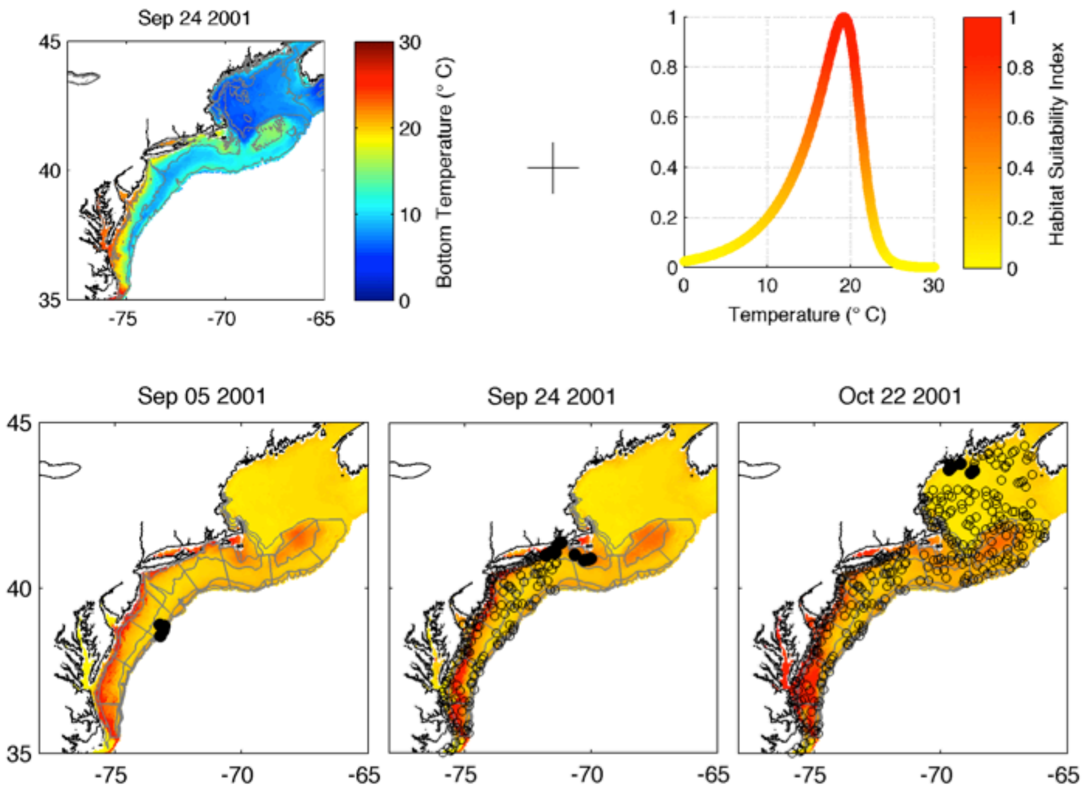

Figure 1. Thermal habitat suitability was projected in space and time by coupling the niche model rescaled from 0 (unsuitable habitat) to 1 (highly suitable habitat) to daily hindcasts of bottom temperature. De-biased ROMS bottom water temperature hindcast for the median date of the 2001 fall NEFSC survey (September 24th; top left) was coupled to a realization of the thermal niche model (top right) to produce a daily hindcast of thermal habitat suitability for butterfish for September 24th, 2001 (bottom middle). Thermal habitat suitability for the first day (September, 5, bottom left) and last day of the fall survey in 2001 (October, 22, bottom right) are also shown. Color scale in habitat suitability plots (bottom panels) is the same as the color scale of the niche model response function (top right). Twenty, 50 and 150 meter isobaths are shown in the bottom temperature hindcast (top left). Lines in bottom panels show offshore NEFSC survey strata included in the assessment. Solid circles in bottom panels indicate NEFSC survey samples taken on the day of the habitat hindcast. Open circles are NEFSC survey samples taken prior to the hindcast date. The habitat suitability projections were used to calculate the proportion of the total habitat suitability in the regional sea sampled at each station on the day of sampling. These values summed across survey stations to estimate the availability of the butterfish stock to the survey as a function of the total available thermal habitat sampled.

Mid-Atlantic Regional Association Coastal Ocean Observing System.

C. Developing Habitat Models:

Based on the interaction we had with the industry through local port workshops and the survey data collected during cooperative trips to the shelf break, we collectively saw the need for targeted model development that could inform the stock assessment of butterfish scheduled in 2014.

We used a thermal niche model coupled to a regional hindcast of bottom water temperatures to develop a habitat-based estimate of availability (ρ_H) as the proportion of thermal habitat for butterfish available in the Northwest Atlantic sampled during a survey. We focused on thermal habitat for the following reasons. First, the high heat capacity and rate of heat transfer of seawater combined with the role of temperature in regulating metabolism and linked vital rates, make temperature the fundamental niche dimension controlling migration dynamics and broad scale distributions of mobile pelagic marine ectotherms like butterfish [2, 3, 4, 5]. Secondly, recent shifts in the distributions of many marine ectotherms are associated with changes in ocean temperature with climate change [6, 7, 8, and many others]. Thirdly, numerical ocean circulation models can now hindcast ocean temperatures accurately enough at resolutions and extents useful for regional marine resource assessment and management.

We built the habitat-based index of availability (ρ_H) of Atlantic Butterfish to assessment surveys in 4 steps: Step 1) a thermal niche model was calibrated using catch and temperature data from fishery independent bottom trawl surveys conducted throughout the Northwest Atlantic; Step 2) a hindcast of bottom water temperature for Northwest Atlantic was constructed using historical climatology to de-bias output from a numerical circulation model; Step 3) butterfish catch data was used to evaluate patterns of sample occupancy in relation to hindcasts of thermal habitat suitability (tHSI) generated by coupling the thermal niche model to hindcast temperatures as well as temperatures measured *in situ* with samples; Step 4) availability (ρ) of the butterfish stock to assessment surveys was calculated using daily regional hindcasts of thermal habitat suitability and the locations and times of survey samples.

III. Thermal Niche Hindcasts

A. Thermal Niche:

To develop a parametric thermal niche model we used the calibration data to estimate parameters for the Johnson and Lewin equation, a unimodal extension of the Boltzmann-Arrhenius function [9, 10; Figure 1]. In the Johnson and Lewin equation:

$$h(T) = ce^{-\frac{E_R}{k_b T}} \Big/ 1 + e^{-\frac{1}{k_b T}\left(E_D - \left(\frac{E_D}{T_{opt}} + k_b \, ln\left(\frac{E_R}{E_D - E_R}\right)\right)T\right)}$$

where the response (h) is a function of absolute temperature (T; degrees Kelvin), a scaling constant (c), the Boltzmann's constant (k_b=8.62x10^{-5} eV K^{-1}, eV=electron volts), the thermodynamic activation energy for the increase in the response with temperature (E_R) up to the optimal temperature (T_{opt}), and the activation energy for decline in the response at temperatures higher (E_D) than the optima. Left skewed asymmetry is produced when $E_R < E_D$. This equation was chosen because it has a basis in temperature dependent enzyme kinetics, can exhibit the left skewed asymmetry typical of thermal performance curves, and has relatively few parameters (N=4) [11]. The left skewed asymmetry of the GAM generated temperature response justified the use of the equation.

We obtained parameter estimates for the niche model from the calibration data by minimizing the negative binomial likelihood of the Johnson and Lewin equation using standardized catch densities as the dependent and bottom water temperatures as the independent variable. We used the bmle library in R [12] and methods described in [13] and [14]. Calculation of the information matrix and uncertainties in parameter estimates required the use of minimal lower boundary constraints (T_{opt}=0, E_R=0.001, E_D=0.002, k=0.001, where k is the size of the negative binomial distribution) in the L-BFGS-B nonlinear optimization method and a fixed scaling coefficient (c). We chose the scaling coefficient based on preliminary maximum likelihood estimation and the height of the GAM-generated temperature response curve, which determined the start value for preliminary estimation. Parameter estimates and the inverse of the information matrix from maximum likelihood were used to generate population prediction intervals and integrate uncertainties in the niche model with uncertainties in bottom temperature [13, 15].

B. Thermal Habitat Suitability:

This niche model was coupled to a hindcast of daily bottom water temperature derived from a de-biased regional numerical ocean model (ROMS) in order to project thermal habitat suitability in the Northwest Atlantic on a daily basis over the last 40 years. The hindcast of thermal habitat suitability was used to estimate the proportion of thermal habitat suitability available on the Northeast US continental shelf that was sampled on fishery-independent surveys conducted during the spring and fall. We were able to create 40 years of daily maps of predicted butterfish thermal habitat suitability (Figure 1). This time series of Habitat Suitablilty was then used to determine a time dependent availability, or stock range, based on butterfish thermal niche space. The time dependent availability was then provided to the stock assessment scientists for inclusion in the model.

C. Availability:

We developed a habitat-based index of the availability (ρ_H) for the butterfish stock that used the thermal niche model coupled to the de-biased bottom temperature hindcast to calculate the proportion of cumulative thermal habitat suitability (*tHSI*) available to the butterfish within the regional sea that was sampled during a survey. The habitat-based index of availability ρ_H was calculated as follows:

$$\rho_H = \sum_{k=1}^{o} \frac{HSI_{k_{j,i}} * \frac{area\ of\ survey\ strata_k}{p}}{\sum_{j=1}^{n} HSI_{j,i} * Area\ of\ j}$$

Here the model based index of habitat suitability (ranging between 0-1) for survey sample k, occurring at location j on day i ($HSI_{k_{j,i}}$) was extrapolated to the spatial area sample k represented in the survey design. This spatial extrapolation was achieved by dividing the *area of the survey strata* (km^2) in which sample k occurred by the total number of samples (p) taken within the strata during the survey. Sample k's suitability index ($HSI_{k_{j,i}}$) was then multiplied by this value to produce an area weighted suitability index. Sample k's area weighted suitability index was then divided by the sum of habitat suitability index values for all locations $j=1...n$ within the model domain for the day for sampling (i) multiplied by their surface areas. The model domain was restricted to bottom depths ranging from 10 to 350 meters between latitudes 35°N to 45°N and longitudes 78°W to 65°W. The surface area of locations was 25 km^2 as defined by the resolution (5 km x 5 km) of coupled niche model-bottom temperature hindcast. Estimates of the proportion of habitat suitability sampled for each station in the survey (k=1…o) were then summed to calculate a habitat-based estimate of the availability of the stock to the survey (ρ_H) (Figure 2).

IV. Application to Stock Assessment

Our multidisciplinary workgroup of experts that included members from fishing industry, government, and academia used data from 7 field surveys throughout the

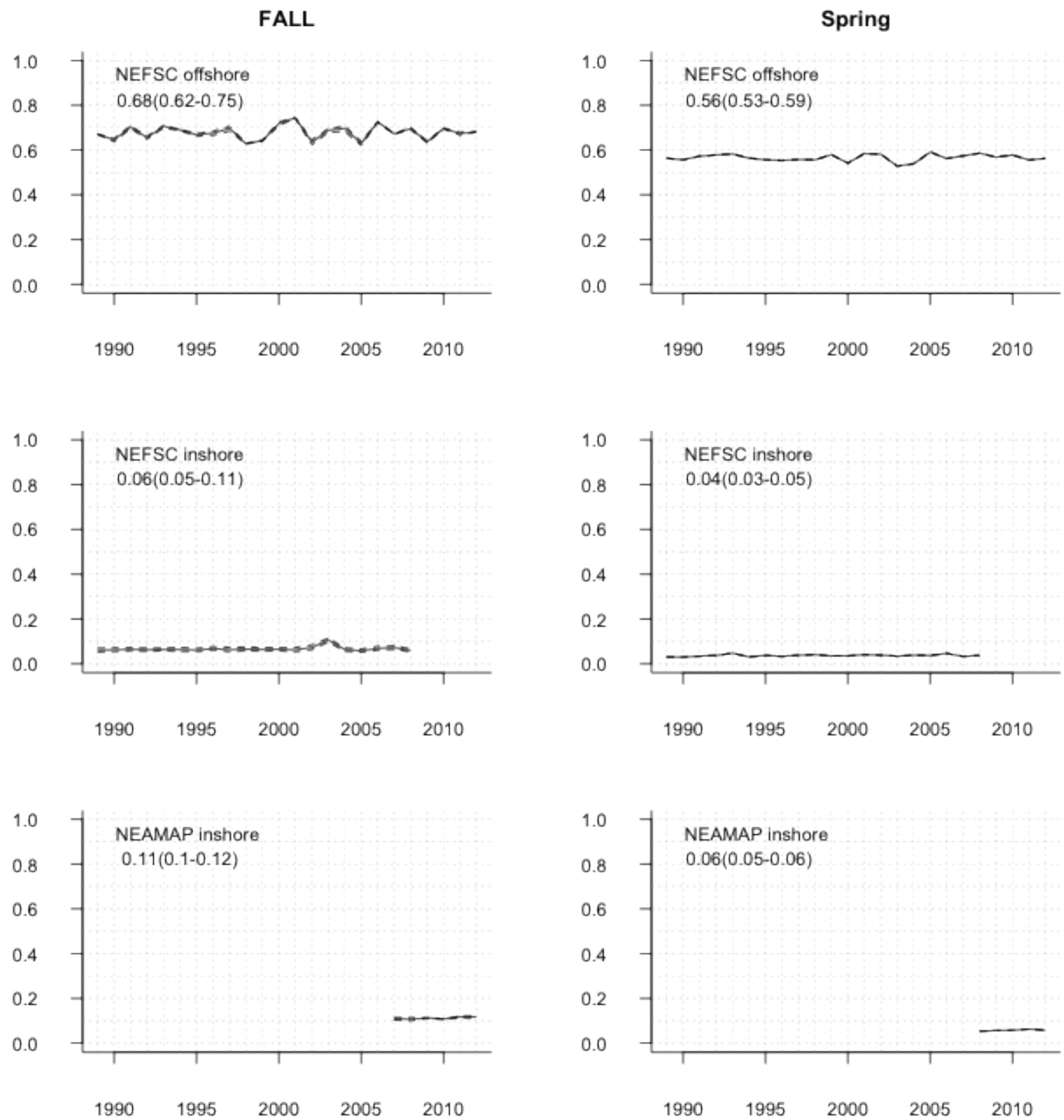

Figure 2. Availability ρ_H of butterfish to spring and fall NEFSC and NEAMAP surveys from 1989 through 2012 calculated as the proportion of available thermal habitat suitability sampled within the model domain estimated using the thermal niche model coupled to the de-biased ROMS bottom temperature hindcast and locations and times of survey samples. Solid line indicates the median estimate while dashed lines show 2.5% and 97.5% confidence intervals. Numbers below survey labels indicate median ρ_H of the time series (95% confidence intervals). NEFSC survey stations were separated into inshore and offshore strata in the assessment.

Northwest Atlantic Ocean to develop a parametric thermal niche model (Manderson et al., 2011) for an important short-lived pelagic forage fish, Atlantic Butterfish (*Peprilus triacanthus*). This niche model was coupled to a hindcast of daily bottom water temperature derived from a de-biased regional numerical ocean model (ROMS) in order to project thermal habitat suitability in the Northwest Atlantic on a daily basis over the last 40 years. The hindcast of thermal habitat suitability was used to estimate the proportion of thermal habitat suitability available on the U.S. NES that was sampled on fishery-independent surveys conducted during the spring and fall. The method explicitly accounted for the relative motions of thermal habitat and the trajectory of sampling on the survey. The method and habitat based estimates of availability was integrated into the catchability estimate used to scale population size in the butterfish stock assessment model accepted by the reviewers of the 59th NEFSC stock assessment review, as well as the Mid-Atlantic Council's Scientific and Statistical Committee. The contribution of the availability estimate (along with an estimate of detectability) allowed for the development of fishery reference points, a change in stock status from unknown to known, and the establishment of a directed fishery with an allocation of 20,000 metric tons of quota.

The result of this effort was a term of reference (ToR) in the 59th NEFSC stock assessment review: *'ToR 3. Characterize oceanographic and habitat data as it pertains to butterfish distribution and availability. If possible, integrate the results into the stock assessment (TOR-5).'* As written in the final report of this review, 'this ToR was met'. The review panel stated that our analysis was 'rigorous and highly innovative.' They go on to say:

*"The primary result of the habitat preference modeling was an index of butterfish availability. For the assessment model, catchability for the NEFSC fall offshore survey was taken to be the product of availability (A) and efficiency (E): q = A*E. Therefore, the annual estimated habitat index values were used to adjust the annual availability of butterfish to the survey, which resulted in a time-series of q values."*

Following the review of our method, *'the Panel strongly recommended continued refinement of the butterfish habitat model, consideration of other potential covariates, and exploration of its use for assessments of other species.'* Following the panel's advice, our method has been included in the SARC 60 assessments of bluefish and scup in 2015.

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