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Influence of oceanographic conditions on the distribution and abundance of blackfin tuna (*Thunnus atlanticus*) larvae in the Gulf of Mexico

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ABSTRACT

Information on early life history of economical important fisheries stocks are required to accurately estimate their population status. This study investigated blackfin tuna (*Thunnus atlanticus*) larvae distribution over six summers (2007–2011, 2015) in the northern Gulf of Mexico. Blackfin tuna were commonly observed and widely distributed in surface waters with frequency of occurrence ranging from 48% (2008) to 92% (2011). Inter-annual variability in density was observed with highest mean density recorded in 2009 (17.2 larvae 1000 m^{-3}) and lowest mean density in 2015 (2.2 larvae 1000 m^{-3}). Density also varied between months with higher overall mean density observed in July (9.2 larvae 1000 m^{-3}) compared to June (4.3 larvae 1000 m^{-3}). Generalized additive models (GAMs) based on presence/absence and density of blackfin tuna larvae determined that this species was present in areas of intermediate salinity (31–36) and higher sea surface temperature (SST $>$ 29 °C). Blackfin tuna larvae were also strongly associated with convergent zones near the Loop Current and anticyclonic eddies. Environmental conditions deemed to be favorable from GAMs (salinity, SST and sea surface height) were combined with environmental data in 2011 and 2015 to predict the suitable habitat of blackfin tuna larvae from the outer continental shelf into oceanic waters (areas $\geq$100 m isobath). The amount of highly suitable habitat ($>$ 10 larvae 1000 m^{-3}) in 2011 and 2015 varied between months (June 6%, July 51%); however, blackfin tuna larvae were predicted to occur at similar locations in surface waters along the continental slope and at the margin of the Loop Current. Overall, the results highlighted the importance of mesoscale features and oceanographic conditions on the distribution and abundance of blackfin tuna larvae.

1. Introduction

The Gulf of Mexico (GoM) supports highly productive commercial and recreational fisheries for tunas (Chesney et al., 2000). Due to overfishing, populations of yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*) and Atlantic bluefin tuna (*Thunnus thynnus*) in this region are decreasing in abundance and are considered to be depleted or fully exploited (Majkowski, 2007; Juan-Jordá et al., 2011). Apart from these taxa, blackfin tuna (*Thunnus atlanticus*) is also an important component of the offshore tuna fishery in the GoM (NOAA, 2016), and despite the numerical dominance of blackfin tuna relative to other tunas, this species has received considerably less attention by the scientific community. Because directed commercial fisheries for tunas in the GoM and western Atlantic Ocean generally target bigeye, bluefin, and yellowfin tuna, the decline of these populations is expected to lead to an increase in fishing pressure on blackfin tuna, which is troubling because no stock assessment or management plan currently exists for this species (ICCAT, 2016).

Understanding the population dynamics of blackfin and other tunas relies on accurate catch or abundance data as well as basic life history information (Fromentin and Fonteneau, 2001; Fromentin and Powers, 2005; Young et al., 2006). Stock abundance of tunas is often predicted using catch rates from a variety of sources (e.g., survey data, reported landings); however, using catch data to estimate key population parameters (e.g., spawning stock biomass) of tunas is problematic because these data are not necessarily reflective of population size, as they represent relative abundance of specific size in particular regions (Maunder et al., 2006). Because most of stock assessments of tunas are based on catch data, environmental and biological factors that affect the population dynamic are typically not integrated in assessment models, which can lead to inaccurately estimated trends in population size (Rouyer et al., 2008; Taylor et al., 2011). New analytical tools have been developed based on fishery-independent measure of abundance taking into account spatial and temporal distribution patterns of exploited species (Lehodey et al., 2003, Lamkin et al., 2015). In particular, larval abundance indices are often used as a proxy or indirect

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means of predicting spawning stock biomass of tunas and other pelagic fishes (Scott et al., 1993; Hsieh et al., 2006; Ingram et al., 2017). Therefore, determining the influence of environmental conditions – both biotic and abiotic – on the spatial dynamics of blackfin tuna larvae is fundamental to assessing their population status.

Blackfin tuna stock status is uncertain in the GoM, as basic information on the spawning and early life habitat of blackfin tuna is limited for this region. Therefore, abundance estimates of blackfin tuna larvae in the GoM can provide critical information that can be used to assess stock status but also determine the timing and location of spawning in this region. It has been observed that potential environmental changes can impact the spatial and temporal dynamics of spawning areas, which influence the distribution and abundance of tuna larvae (Lindo-Atichati et al., 2012; Reglero et al., 2014). The northern GoM has been described as an essential spawning and nursery habitat of blackfin tuna (Rooker et al., 2013; Cornic et al., 2018), and the distribution and abundance of tuna larvae has been related to seasonal variations in the geographic position of the Loop Current and physicochemical conditions associated with this feature (Lindo-Atichati et al., 2012; Muhling et al., 2013). Due to the fact that physicochemical conditions of a nursery habitat are known to influence the growth and survival of tuna larvae (García et al., 2013; Kim et al., 2015), it can be expected that oceanographic features associated with early life habitats of blackfin tuna will affect their growth, survival, and recruitment. Therefore, defining environmental factors associated with early life habitats and the location of putative production zones for blackfin tuna is essential to understanding the influential drivers of recruitment success for this species in the GoM.

The objective of this study was to characterize the spatiotemporal patterns in distribution and abundance of blackfin tuna larvae in surface waters of the northern GoM. Because the distribution and abundance of tuna larvae depend on environmental factors of their habitat, generalized additive models (GAMs) based on presence-absence (P/A) and density were developed to determine the most influential environmental parameters affecting blackfin tuna larvae. Explanatory variables from GAMs were used to predict the distribution of blackfin tuna larvae based on environmental conditions in 2011 and 2015, and the estimated probabilities were then used to characterize the spatial extent and areal coverage of suitable habitats of blackfin tuna larvae in each year.

2. Materials and methods

2.1. Sampling protocol

The Gulf of Mexico (GoM) is semi enclosed sea, and oceanographic conditions off its continental shelf are generally oligotrophic and influenced by the Loop Current, a warm surface waters moving from the Caribbean Sea to the Atlantic Ocean through the GoM and the Florida Strait (Fig. 1). The Loop Current expansion in the GoM is highly variable and generates anticyclonic and cyclonic eddies that can affect the sea surface temperature and productivity of its region (Muller-Karger et al., 2015). Apart from the Loop Current, the northern GoM is influenced by seasonal riverine discharges from the Mississippi River that can modify the physicochemical characteristics (i.e salinity, turbidity) and productivity on the continental shelf and slope (Dagg et al., 2004).

Ichthyoplankton surveys were performed in June and July from 2007 to 2011 and 2015 in the northern GoM (Fig. 1). Blackfin tuna were collected in surface waters using neuston nets (1 m × 2 m frame) with 80% of the mouth of the net below the water. Therefore, larval densities were calculated under the assumption that neuston nets sampled at an average depth of 0.8m. From 2007–2010 two neuston nets with different mesh sizes (500 and 1200 μm) were used, while only one neuston net (1200 μm) was deployed in 2011 and 2015. Nets were deployed during the day for a duration of 10 min at an approximate speed of 1 ms^{-1}, with deployments being made every 15 km in order to

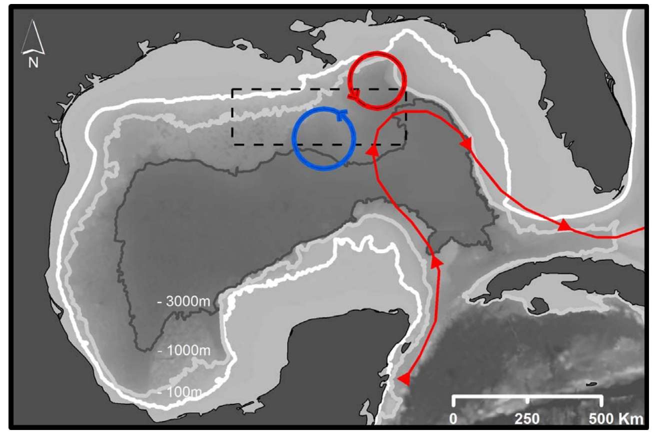

Fig. 1. Sampling area (dashed rectangle) of the June and July ichthyoplankton cruises performed from 2007 to 2011 and 2015 in the northern Gulf of Mexico. General oceanography of the Gulf of Mexico is represented by the Loop Current (red line), anticyclonic eddy (red circle), and cyclonic eddies (blue circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sample diverse oceanographic features. Each net was equipped at its center with a General Oceanic flowmeter (Model 2030R, Miami, FL) to estimate the volume of water sampled. All fish larvae were fixed on board in 95% ethanol and later preserved in 70% ethanol.

2.2. Environmental data

Sea surface temperature (SST, °C) and salinity were recorded at each sampling station (n = 325) from the research vessel using a Sonde 6920 Environmental Monitoring System (YSI Inc.). Also, *Sargassum* biomass (wet weight in kg) collected in neuston nets was recorded at each station. Additional environmental data at each station were extracted from open access resources using the Marine Geospatial Ecology Toolbox in ArcGIS (Roberts et al., 2010). Sea surface height anomaly (SSHA, cm) data were determined from remotely sensed data that matched our sampling dates and station locations. Sea surface height anomaly data were generated every 7 days (d) from combined satellite altimetry measurements using Jason-1 and 2, ENVISAT/ERS- 1 and 2, Geosat Follow-On and Topex/Poseidon inter- laced (AVISO). Sea surface chlorophyll *a* concentrations (mg m^{-3}) were accessed from NASA Ocean Color Group's Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite. Chlorophyll *a* concentration data consisted of 8 d averaged time periods with a 1/24° resolution. Water depth (m) at sampling stations was obtained from NOAA's NGDC U.S. Coastal Relief Model. To generate predicted suitable habitat of blackfin tuna larvae in June and July 2011 and 2015, environmental data (SSHA, SST, salinity) were extracted from remotely sensed observations using a grid of 0.0833°. SSHA were estimated from AVISO, while SST and salinity were extracted from the Gulf of Mexico Hybrid Coordinate Ocean Model (GoM-HYCOM) and added to U.S. Navy Coupled Ocean Data Assimilation (NCODA) system.

2.3. Larval identification

At the laboratory, *Thunnus* larvae were visually sorted using morphological characteristics and pigmentation (Richards, 2006). Because *Thunnus* larvae were abundant (n = 16986) in our samples, only positive stations (*Thunnus* present) containing more than 10 larvae were genetically identified. A subset of 6974 *Thunnus* larvae from 61% of the overall positive stations (n = 530) were selected across the main areas of our sampling corridor (27–28°N transect) and/or oceanographic features for each survey. Then, each larva was genetically identified to the species level using high-resolution melting analysis (HRMA), following the protocol described by Cornic et al. (2018). At stations with