1.3.5 Biophysical Interactions Driving Tuna Larvae Presence in Cuban Waters in the Gulf of Mexico: Recent Efforts by NOAA/SEFSC, NOAA/AOML and UM/RSMAS/CIMAS

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1.3.5.1 Abstract

Bluefin tuna and other tuna species are crucial economic and ecological resources of the northern Atlantic. Although the GOM is a known spawning ground for bluefin tuna, little is known about bluefin spawning activity in the southern Gulf, especially in Cuban waters, and there is little information concerning spawning activity of other tuna species such as yellowfin and skipjack tuna. The specific ocean circulation of the Gulf, dominated by the Loop Current, is expected to play a role in the distribution of tuna larvae in the region, but the extent of these biophysical interactions is not precisely known. Two cruises were led by NOAA in spring 2015 and spring 2016, in collaboration with scientists from Mexico and Cuba, to elucidate the patterns of Atlantic bluefin tuna spawning, and their connection to local circulation. Scientists at the University of Miami provided real-time model simulations of ocean circulation, which were useful for analyzing features of interest that might influence local and regional biophysical connectivity.

1.3.5.2 Introduction

Atlantic bluefin tuna (*Thunnus thynnus*) spawn in late April to early June in the GOM at temperatures above 23 °C (Richards 1976). Spawning activity is primarily focused in the north-central GOM. However, bluefin tuna larvae have also been reported from the Straits of Florida (Richards and Potthoff 1980; Brothers et al. 1983; Figure 35), southwest GOM (Olvera Limas et al. 1988), and along the East Coast of the United States as far north as the Carolinas (McGowan and Richards 1989). Recent work has suggested that bluefin may also spawn off the Yucatan coast of Mexico, as well as north of the Bahamas (Muhling et al. 2011; Lamkin et al. 2014). The extent and frequency of spawning in these outlying habitats is unknown. Blackfin (*T. atlanticus*), yellowfin (*T. albacares*), and skipjack (*Katsuwonus pelamis*) tuna also spawn in the GOM and western Caribbean and, though not as economically important as bluefin, they play a critical ecological role both as food fish and as top predators. Samples collected as part of NOAA's Southeast Area Monitoring and Assessment Program (SEAMAP) suggest blackfin tuna are ubiquitous in the ichthyofauna of the northwestern GOM. Less is known about yellowfin and skipjack tuna, which are observed frequently but are not as widely distributed. Outside of the area surveyed in the nothwestern GOM, little is known about the ecology and distribution of these species in the southern GOM. Of particular interest is the potential spawning activity of bluefin tuna north and south of Cuba.

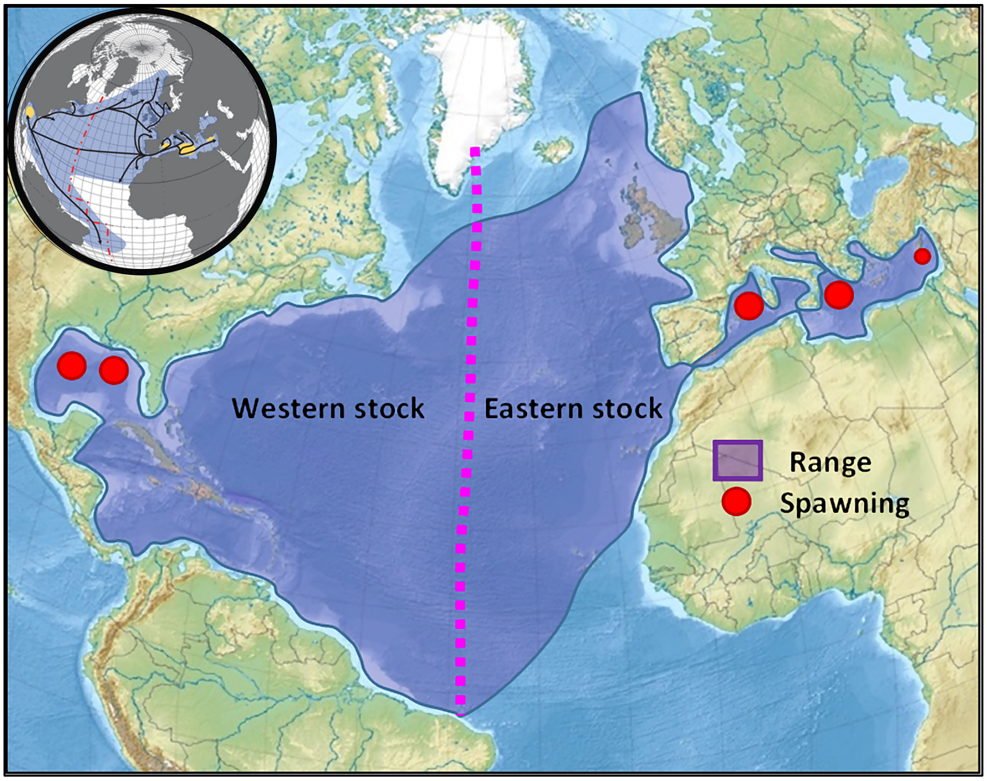

Figure 34. Atlantic bluefin tuna migrate from the North Atlantic to spawn in the summer.

Adult bluefin tuna are distributed throughout the North Atlantic and are exploited with a variety of fishing gears throughout their range. The western Atlantic bluefin stock is estimated to have declined precipitously during the 1970s and early 1980s, but it has been relatively stable since the implementation of quotas in 1982. The NOAA Southeast Fisheries Science Center (SEFSC) has developed a fishery independent index for the western bluefin stock using larval bluefin tuna abundances from annual ichthyoplankton surveys. These surveys have been carried out since the late 1970s, and since 1982 have been completed as part of the SEAMAP program (Scott et al. 1993, Ingram et al. 2010). The larval index is an important component of the bluefin stock assessment, as well as the development of habitat models to improve the index (Lamkin et al. 2015). However, an effective index should account for significant spawning outside the survey area, so it is important to determine the extent of spawning habitat in adjacent oceanographic areas, such as Cuba.

The NOAA National Marine Fisheries Service (NMFS) has a long but infrequent history of biological sampling near Cuba dating back to the Deep Sea Research expedition in 1919. The oceanographic and fisheries vessel *Albatross* conducted sampling at a series of plankton stations from the Florida Keys to Havana, and across the Yucatan Channel; the samples are archived in the Smithsonian Museum of Natural History. However, these sampling efforts were sporadic and there has not been a systematic effort to sample for bluefin and other tuna larvae by the United States. Other efforts were historically made to sample for adult tuna south of Cuba, such as Bullis and Mather’s (1956) collection of adult bluefin tuna in April 1955. These surveys were not repeated, and the extent of bluefin habitat in the western Caribbean and the Florida Straits is unclear.

Interest in larval bluefin spawning habitat around Cuba had been growing as the SEFSC and the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) further refined the larval index and sought to understand the extent of spawning outside the GOM. Little is known about the ichthyoplankton in the region, or the mesoscale physical oceanographic features that drive productivity (see Figure 35). Understanding the biological-physical connection and drivers of recruitment is a priority to the SEFSC and key to understanding bluefin larval dynamics. As a result of these interests, NOAA (SEFSC, AOML) proposed conducting larval/physical oceanography surveys around Cuba and developed a collaboration with scientists from Mexico (ECOSUR) for sampling physical parameters and analyzing ocean circulation patterns. In 2014, Cuba agreed to allow sampling within their waters and participated in NOAA-led cruises in 2015 and 2016. These surveys sampled the waters around Cuba and the Yucatan extensively in 2015 and concentrated on northern Cuba in 2016 (Figure 36). Mexico and the United States signed a Memorandum of Understanding (MOU) for MPA conservation and management in 2012, which favors the establishment of a sister sanctuary relationship in the region. More recently, the United States and Cuba established relationships between Guanahacabibes National Park and Banco de San Antonio in Cuba, and the Florida Keys National Marine Sanctuary and the Flower Garden Banks National Marine Sanctuary in the United States under the MOU signed in November 2015. All of these MPAs are connected by the regional ocean circulation.

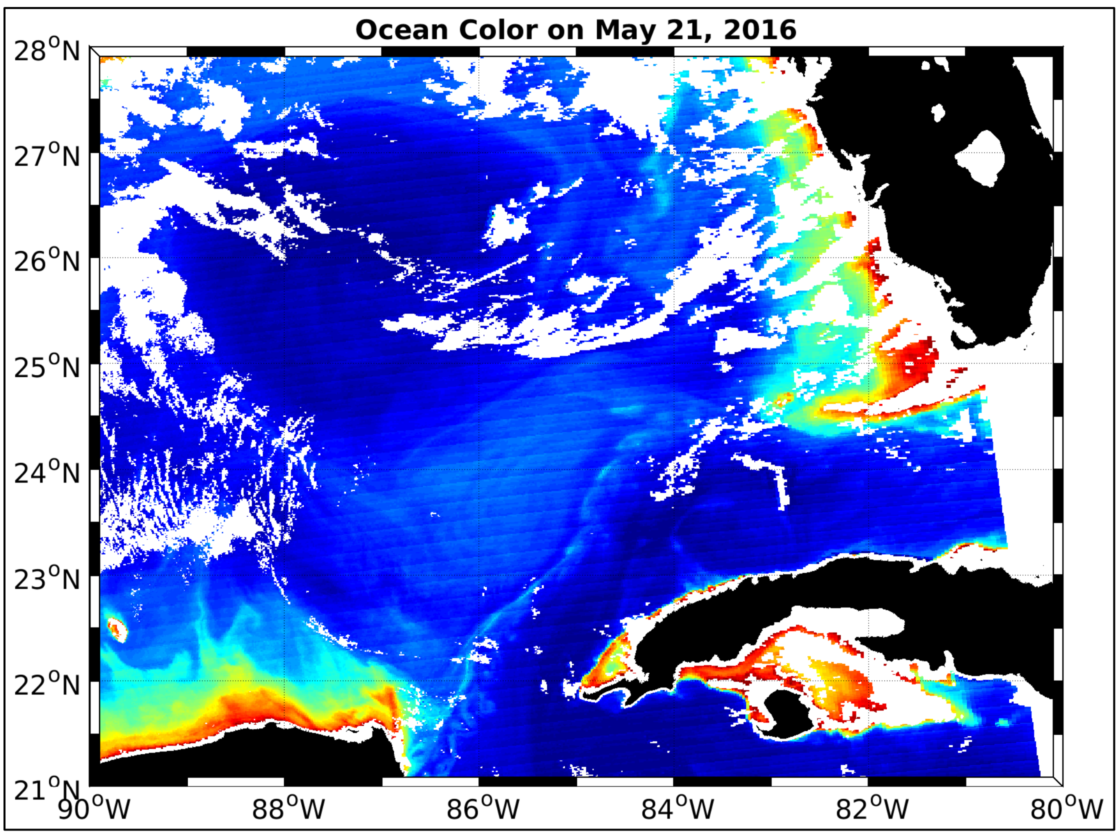

Figure 35. Chlorophyll-*a* (Chl-*a*) in the Southeastern GOM on May 21, 2016, during the NOAA cruise around Cuba.

Chl-*a* map is from Modis Aqua, and color shading indicates relative Chl-*a* values from low (blue) to high (red). Source: University of Southern Florida College of Marine Science Optical Oceanography Lab.

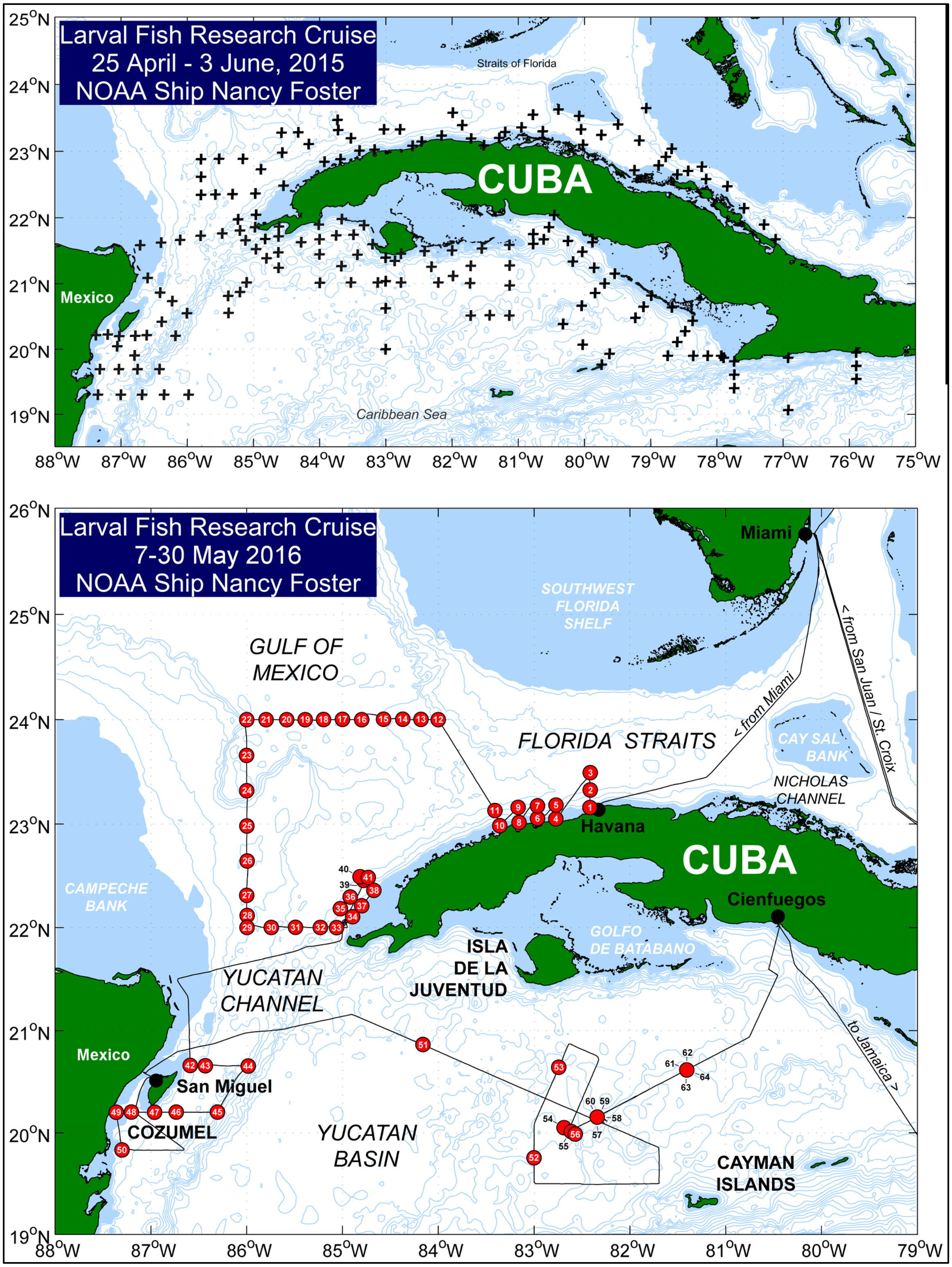

Figure 36. 2015 cruise sample locations (upper); 2016 cruise sample locations and survey tracks (lower).

Collaboration with oceanographers at the University of Miami and NOAA/AOML supported the analysis of oceanic circulation that drives the connectivity among GOM coastal and deep ecosystems. The dominant circulation feature that affects the Cuban waters within the GOM is the Loop Current (LC), which is the local portion of the North Atlantic western boundary current. The LC enters the GOM via the Yucatan Channel between Mexico and Cuba, and exits at the Straits of Florida, between Cuba and Florida, where it becomes the Florida Current, and finally the Gulf Stream along the southeastern United States. The pathway of the LC within the GOM varies in time, from a retracted, or port-to-port position, to an extended position. In its retracted position, the LC flows almost directly from the Yucatan Channel to the Straits of Florida, and through most of the northwestern Cuban waters. In its extended position, the LC flows northward and reaches the edge of the northern GOM continental shelf near the Mississippi Delta, before turning clockwise and southward toward the Florida Straits. When extended, the LC eventually closes its clockwise circulation, resulting in the formation of a large, warm-core eddy that then drifts westward inside the GOM, before dissipating when interacting with the western GOM shelf and coasts. After shedding a warm-core eddy, the LC typically retracts to the port-to-port position. The eddy shedding frequency is highly variable, 2–19 months, with most frequent occurrences at 6, 9, and 11.5 months (Leben 2005). The eddy shedding sequence often involves temporary detachments and re-attachments of the warm-core eddy, before final separation (Schmitz 2005). Small, cold-core eddies with anticlockwise rotation form and propagate at the outer edge of the LC and play a role in the detachments and separations of LC warm-core eddies (Fratantoni et al. 1998; Chérubin et al. 2005, 2006; Le Hénaff et al. 2012, 2014; Athié et al. 2012). These cold-core eddies also affect the meandering of the Florida Current in the Straits of Florida, so that when one of these eddies is present on the northern side of the current, the current is deflected toward Cuba (Fratantoni et al. 1998; Kourafalou and Kang 2012). As a result, all of the LC stages affect the ocean circulation over northwestern Cuban waters.

Understanding the relationship between the abundance and distribution of bluefin tuna larvae and the ocean circulation is even more difficult in the Cuban waters of the GOM, as aside from the general LC circulation, smaller scale circulation features are poorly understood in this area. Indeed, due to the geopolitical situation regarding Cuba in the past decades, there have been almost no in situ physical oceanography data collected in Cuban waters which are publicly available to the international scientific community to study the local circulation. An exception occurred with the collaboration between Cuba and Mexico to measure the transport associated with the incoming LC in the Yucatan Channel, which allowed a countercurrent toward the Caribbean Sea along the Cuban coasts to be identified (Ochoa et al. 2001). However, the circulation along the Cuban coasts north of the Yucatan Channel is still poorly known. In addition, despite the availability of satellite data and the possibility of using numerical models in that region, there are very few studies that focus on, or even mention specific circulation patterns around Cuba. A recent study by Kourafalou et al. (2017), based on remote sensing and numerical modeling, identified clockwise circulation eddies, named Cuban Anticyclones (CubANs), that form at the base of the LC close to the Cuban coasts and propagate eastward in the Straits of Florida, affecting the meandering of the LC and the Florida Current. These CubAN eddies tend to form when the LC is retracted and are sometimes found together with cold-core filaments or eddies associated with coastal upwelling (Kourafalou et al. 2017).

Thus, the objectives of the 2015 and 2016 research surveys that focused on the GOM bluefin tuna ecosystems were to: a) characterize the presence of bluefin tuna larvae in Cuban waters, b) characterize the ocean circulation processes in these waters, and c) improve our understanding of the interactions between the ocean circulation and the biology affecting bluefin tuna. Preliminary data from 2015 are presented here; samples from 2016 have been sorted, but not yet identified. In addition, the authors would like to note that these surveys are only a snapshot of the biological and physical processes in an ecologically complex region. A longer-term collaborative research effort is needed to develop an understanding of the regional complexities and the biological connections linking the western Caribbean and the GOM, including the Florida Straits. How the data used for the study were collected is presented in the next section, followed by sections detailing the preliminary results related to the cruises objectives, and providing conclusions and recommendations for future research related to this topic.

1.3.5.3 Data Collection

The survey work associated with both the 2015 and 2016 cruises included shipboard zooplankton samples collected with a 1 m × 2 m 505 µm mesh plankton net towed from the surface to 50 m, and additional tows that just sampled the upper 10 m. Zooplankton was also collected with a mini bongo with a 200 µm and 30 µm mesh net, as well as a Multiple Opening and Closing Net Environmental Sensing System (MOCNESS). Conductivity-Temperature-Depth (CTD) casts measuring temperature, salinity, dissolved oxygen, chlorophyll, colored dissolved organic matter (CDOM), and water velocity were collected at each station. Continuous surface measurements of temperature, salinity, chlorophyll, CDOM, and water velocity were also collected via the ship's flow-through system and hull-mounted 150 kHz Acoustic Doppler Current Profiler (ADCP). Satellite-tracked, Lagrangian surface drifters were also deployed to study the regional circulation. Satellite imagery of sea surface temperature, altimetry, and ocean color data are used to aid in the interpretation of shipboard data and drifter observations.

In addition to these observational data, we have access, through the Ocean Modeling and OSSE Center (OMOC) between NOAA-AOML and the Rosenstiel School of Marine and Atmospheric Science (RSMAS) of the University of Miami, to two model simulations in order to analyze some of the circulation patterns observed in Cuban waters. These simulations are based on the HYbrid Coordinate Ocean Model (HYCOM). The first simulation covers the full GOM at 1/50° (~2 km) resolution and has data assimilation capabilities (Le Hénaff and Kourafalou 2016). The second simulation (FKEYS) is centered over the Straits of Florida, with a higher resolution of 1/100° (~900 m) and is nested in the operational Navy GOM simulation (Kourafalou and Kang 2012). The FKEYS simulation has been used to study CubAN eddies (Kourafalou et al. 2017). Both model configurations are currently run in near real time.

1.3.5.4 Results

1.3.5.4.1 Physical Processes

In 2015, the cruise sampled the GOM Cuban waters at a time of extended LC during late May–early June. The cruise sampled the Yucatan Channel, then the GOM Cuban waters from West to East (Figure 36, upper panel). The onboard ADCP data show the intense anticyclonic circulation associated with the LC northwest of Cuba, as the direction of the current shows a marked clockwise circulation. The LC is also clearly visible in satellite altimetry, as it is associated with an elevated sea surface height (SSH). In the Florida Straits, the ADCP data record the intense flow of the Florida Current very close to the Cuban coasts, associated with a meandering of the current clearly seen in the altimetry. Such meandering of the Florida Current, usually associated with the presence of cyclonic eddies north of the current (Fratantoni et al. 1998; Kourafalou and Kang 2012), strongly affects the local circulation in Cuban waters. Examination of ocean color data on 21 May 2015 (Figure 37, upper panel) shows the presence of a filament of elevated surface chlorophyll-*a* (Chl-*a*), a portion of which seems to originate from the western tip of Cuba, just offshore the Gulf of Guanahacabibes. This filament is entrained along the LC toward the northwest and the GOM interior. The onboard ADCP data show a short cyclonic veering of the current just south of the LC associated with the filament. The orientation of the coast at that location and the dominant winds are favorable for upwelling, which is usually associated with cyclonic activity (Kourafalou et al., 2017). This is consistent with the ADCP observations.

In 2016, the GOM section of the cruise started from Havana and sampled Cuban waters to the west, toward Mexico (Figure 36, lower panel). At that time, the LC had just shed a large, warm-core anticyclonic eddy. The 2016 cruise was able to sample the very large LC frontal cyclonic eddy that took part in the LC warm-core eddy separation. The ADCP sampled the cyclonic circulation patterns (Figure 37, lower panel). Ocean color imagery shows elevated Chl-*a* levels within this cyclonic eddy, compared to surrounding areas. Drifters were deployed at the core of the eddy. The shedding of the LC warm-core eddy was associated with the retraction of the LC to its southern position, which makes the 2016 conditions very different from the 2015 cruise.

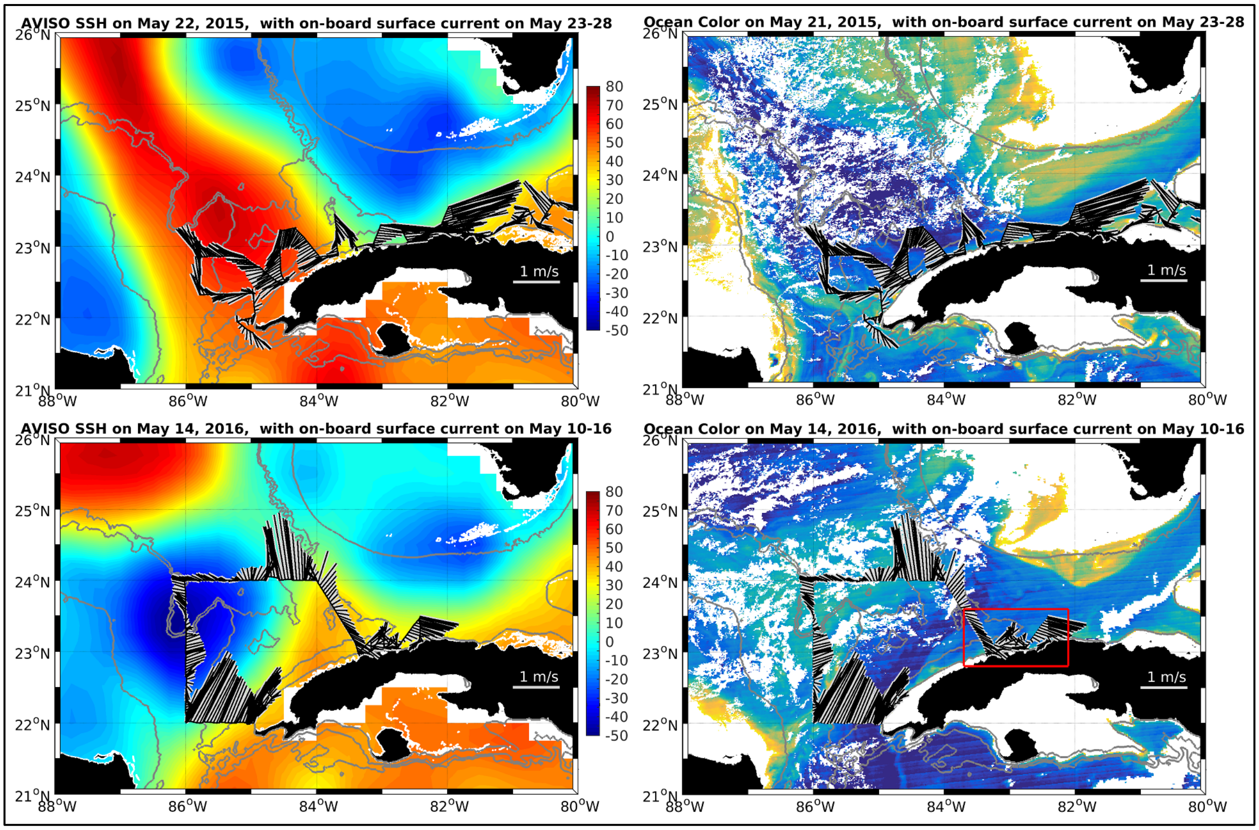

Figure 37. SSH and Chl-*a* concentrations for May 2015 (top) and May 2016 (bottom).
SSH (cm) is from AVISO altimetry observations on 22 May 2015 (top) and 15 May 2016 (bottom) with surface ADCP current vectors on 21 May 2015 (top) and 14 May 2016 (bottom). Figures include surface current vectors (black and grey lines), selected isobaths (light grey lines at 200 m, 2,000 m, and 3,000 m), and the area for the zoom on Figure 38. Chl-*a* maps (right) are from Modis Aqua, and color shading indicates relative Chl-*a* values from low (blue) to high (orange). Source: University of Southern Florida College of Marine Science Optical Oceanography Lab.

The cruise also sampled small-scale processes along the coast of Cuba. Just west of Havana, the survey cruise sampled a filament of high Chl-*a* waters also evident in the concurrent remotely sensed data (Figure 38, upper panel). The onboard ADCP indicates a localized offshore current, surrounded by anticyclonic current veering east of the filament, and a cyclonic current veering west of it, where the high Chl-*a* was observed. The cyclonic circulation pattern and the presence of high Chl-*a* waters are typical of coastal upwelling. The anticyclonic circulation pattern is consistent with the formation of anticyclonic eddies along the northern coasts of Cuba (Kourafalou et al. 2017). Figure 38 (lower panel) shows the presence of a similar pattern in the near-real-time GOM-HYCOM 1/50° simulation during the same period. The simulated sea surface temperature (SST) is lower west of the jet, consistent with the presence of upwelling. The simulated currents show similar patterns of anticyclonic and cyclonic circulation patterns forming an offshore jet, as observed during the 2016 cruise. Similar circulation patterns are also seen in the FKEYS-HYCOM 1/100° simulation. Figure 39 shows the presence of small-scale anticyclonic and cyclonic eddies along the coast of Cuba, with offshore jets forming in between, similar to those observed during the 2016 survey.

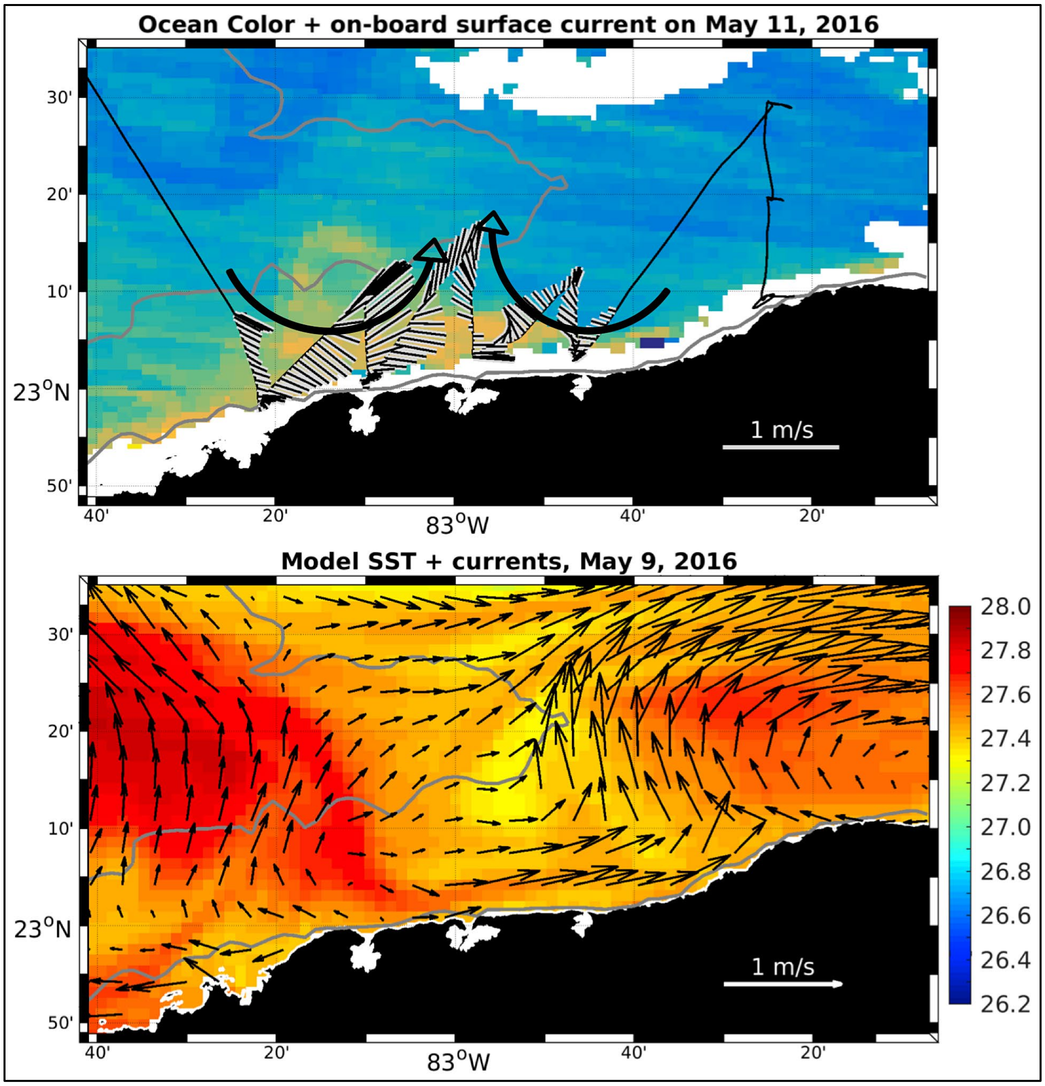

Figure 38. Chl-*a* and surface ADCP current vectors (upper) on 11 May 2016 and SST (lower) on 9 May 2016.

ACDP current vectors are black and grey lines (see figure for reference vector) with the large black round arrows illustrating the current circulation. SST) (°C, colors) and surface currents (black arrows, see reference arrow over Cuba) are from the GOM-HYCOM near-real-time simulation at 1/50°.

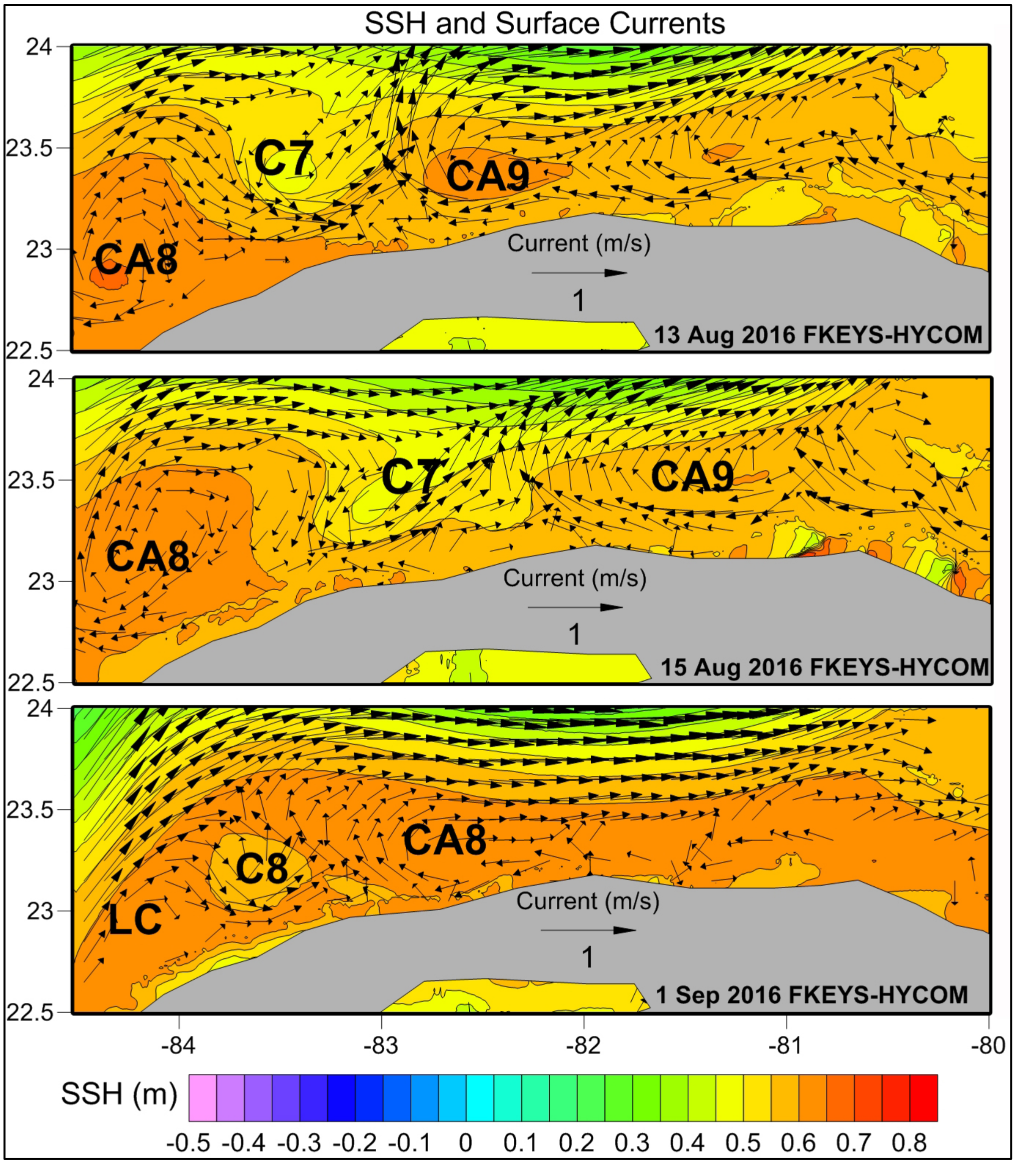

Figure 39. Simulated SSH and surface currents in late summer 2016: 13 August (top), 15 August (middle) and 1 September (bottom).

SSH (m, in colors) and surface currents (black arrows, see reference arrow over Cuba), from the 1/100° FKEYS-HYCOM simulation. CA = CubAN anticyclonic eddy; C = cyclonic eddy; and LC = Loop Current. Adapted from Kourafalou et al. (2017).

1.3.5.4.2 Biology

During the 2015 cruise, larval fish distributions were concentrated around areas of high productivity, such as Jardínes de la Reina and Guanahacabibes, as well as the northwest Cuban coast (Figure 40). In addition, high abundances were found at stations along the north coast of Cuba and south of Cay Sal Bank. Tunas, snappers, and parrot fish dominated the ichthyofauna, with large densities of snapper (>1,000 m^{-3}) collected at shallower (<200 m) inshore stations in the south and along the northwest coast. Lion fish (*Pterois* spp.) were relatively common in the ichthyofauna with higher numbers found to the south, but also present along the northwest coast of Cuba. *Thunnas* spp. were captured throughout the area, and skipjack larvae were caught at 61 of the 185 stations (33%), whereas blackfin larvae were caught at 130 stations (70%). Larval abundance of skipjack larvae was highest off Mexico and in the

Yucatan Channel (Figure 41, upper panel). Abundance of blackfin larvae was highest off the northern coast of Cuba, but high concentrations were also found in the Caribbean Sea between the Isla de la Juventud and Cabo Cruz (Figure 41, lower panel). Larval abundance of both species was lowest off Jamaica.

Abundance of skipjack larvae was greater at night than during the day. This finding suggests that skipjack exhibit some form of diel vertical migration. Thus, although the gear used works well to capture other tuna species, oscillations to a deeper depth may work better to capture skipjack larvae. Abundance of blackfin larvae increased as SST increased from ~26.75 to ~28.5 °C and decreased as chlorophyll concentration increased from ~0.068 mg/L to 0.080 mg/L, at which point larval abundance declined. Bluefin tuna were not a significant part of the tuna ichthyofauna and their distribution will be described in a later publication.

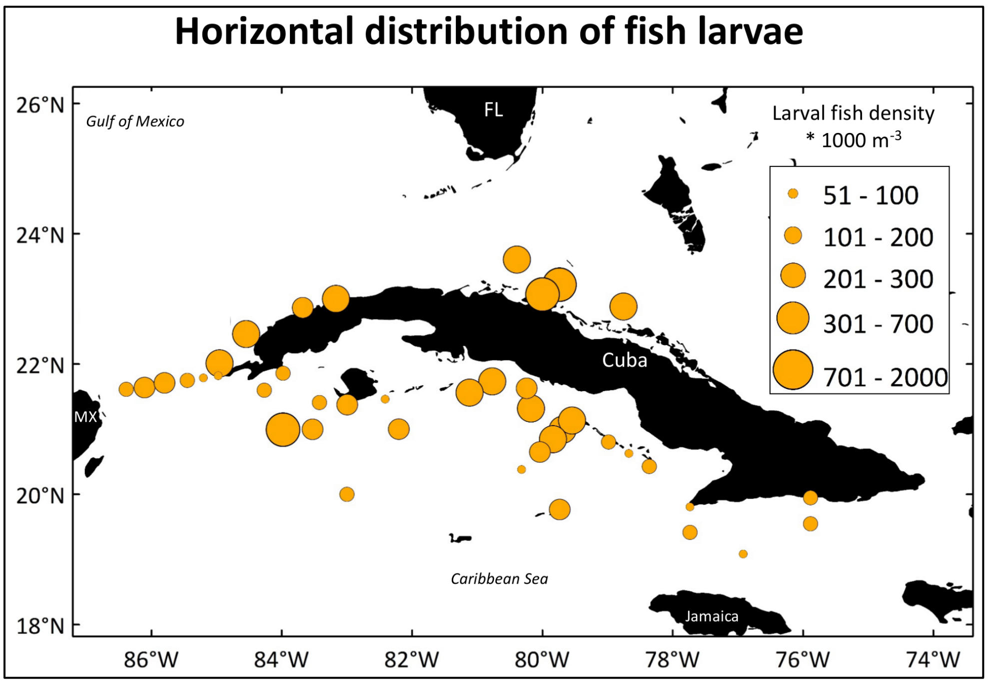

Figure 40. Distribution of larval fish from the 2015 cruise.

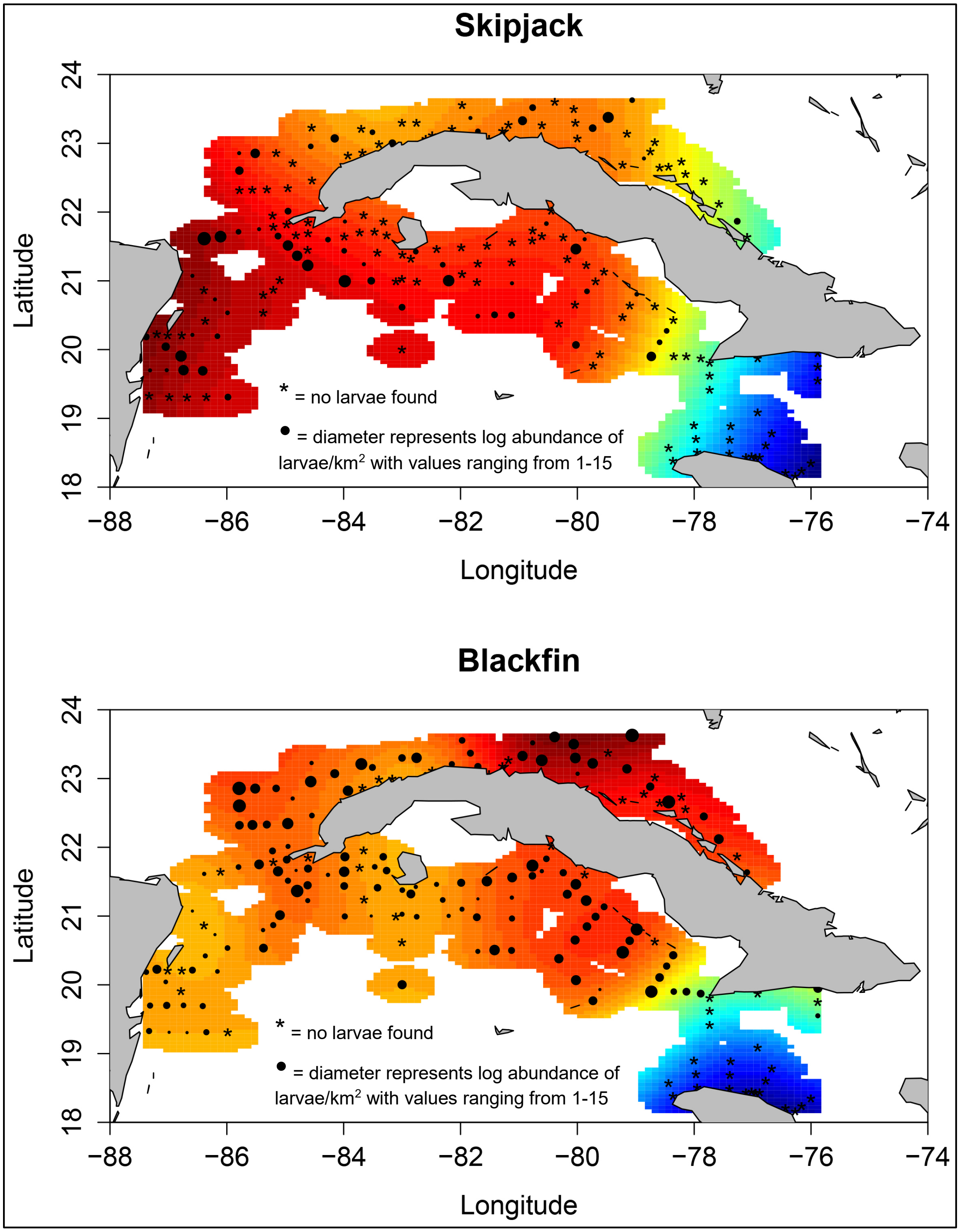

Figure 41. Location and abundance of skipjack and blackfin tuna.

1.3.5.5 Conclusions

Larval transport, dispersal and oceanographic connectivity are, generally, poorly understood. Even less is known about dispersal curves, behavioral components, and temporal and spatial variability of marine larvae. Larvae are entrained in western boundary currents, such as the Gulf Stream, as evidenced by the tropical fauna found seasonally as far north as Massachusetts (Robins et al. 1986). Reef fish larvae are also found in ichthyoplankton samples collected in LC waters in the northern GOM. However, the degree to which tropical larvae are dispersed poleward by ocean currents is unclear. Transport pathways between the waters off Yucatan and Cuba (including fish spawned south of Cuba) and the Florida Keys could be as short as 1–5 days. Results from these cruises and ancillary data from drifters and remote sensing show that the study areas—coastal Yucatan and Cuba, the GOM, and the Florida Keys reef tract—are oceanographically connected, with relatively rapid transport time-scales. Furthermore, eddies and gyres may play an important role in establishing the relevant time and distance scales of connectivity. Such direct physical connectivity by means of ocean currents between the highly migratory species, such as tuna, as well as coral reef biota of these geographically separated spawning grounds, may have an important influence on the degree of biological connectivity between regional populations of ecologically and economically important tropical marine species. As noted in the introduction, these two research cruises provide a snapshot of the ecology and physical processes of the region, but do not begin to unravel the complexities of the biophysical interactions affecting larval transport and exchange in this area. However, the international collaboration between Mexico, Cuba and the United States allowed significant gains to be made in identifying basic processes, larval fish distribution, and the physical processes that act to control the strength of biological connections between these areas.

1.3.5.6 Acknowledgments

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1.3.5.7 References

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