From Movements to Management: Regional Connectivity of Dolphinfish (*Coryphaena hippurus*) in the Northeastern Caribbean Sea

De Los Movimientos a la Manejo; Conectividad Regional de Dorado (*Coryphaena hippurus*) en el Mar del Noreste del Caribe

Des Mouvements À La Direction : La Connectivité Régionale De La Dorade Coryphène (*Coryphaena Hippurus*) Dans La Mer Des Caraïbes

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ABSTRACT

Dolphinfish (*Coryphaena hippurus*) movements relative to the Greater Antilles and northern Lesser Antilles were examined using conventional (n=540) plastic dart tags and pop-up satellite archival tags (n = 6) from 2002 - 2013. The overall recapture rate for fish released (73 - 130 cm FL) within the NE Caribbean was 2.7% (n = 15) with days at liberty (DAL) and movement rates ranging from 1-557 d, and 2.2-29.1 km/d, respectively. Regional movements were westward (274.42º ± 21.06º; mean ± SD) and the maximum distance recorded was 1,917 km between San Juan, Puerto Rico, and Charleston, South Carolina. Six fish were recaptured in the Caribbean Sea after being released off of Florida (n = 5) and South Carolina (310 ± 127 d). Fish movements were compared to surface drifter tracks (n = 196) in the region. Both dolphinfish and drifter movement rates were faster in the Caribbean Sea than in the tropical Atlantic (north of Greater Antilles). Entry of drifters into the Caribbean Sea from the Atlantic Ocean occurred through the northern Lesser Antilles, the Anegada Passage, and the Mona Passage; the latter exclusively appears to be both an entry and exit. These features are likely movement corridors for dolphinfish. Results suggest return migrations towards the Loop Current (south of the Greater Antilles) or Straits of Florida (north) and the Gulf Stream. Understanding dolphinfish movements and population connectivity among exclusive economic zones of northern Caribbean islands and the United States is critical for accurate assessments of fishing mortality, spawning biomass and stock health, and management must be viewed within a regional context.

KEY WORDS: Dolphinfish, fisheries management, return migrants, population connectivity

INTRODUCTION

Dolphinfish is a mid-trophic level pelagic fish of significant importance to artisanal, recreational, and commercial fisheries throughout the world's tropical and subtropical oceans (Parker et al. 2006). Mahon (1999) provided a comprehensive review of direct and indirect fishing effort for dolphinfish in the western central Atlantic from 1950 - 1995 and reported that overall, fishing pressure and landings (from artisanal, small and large-scale commercial, and recreational) increased throughout the time-period. Due to an increase in recreational fishing participation (Parker 2006) and commercial operations (Mahon 1999, SAFMC 2003), the trend for higher fishing pressure and landings continues (Parker 2006).

In the United States (i.e. Atlantic coast, Gulf of Mexico, and Caribbean Sea), recreational and commercial landings from 1980 to 2005, and 1955 to 2005, increased from 1.8 million, and 272,700 kg/yr, to 4.5 - 6.3 million, and 636,363 kg/yr, respectively (Parker 2006). In the northeastern Caribbean Sea around Puerto Rico, landings for artisanal, recreational, and commercial operations was estimated at 305,000 kg/yr in 1979 (CFMC 1983); recently, an analysis of the activity and harvest patterns in Puerto Rico's marine recreational fisheries found that from 2009 to 2013 recreational fisheries (privately owned vessels) alone landed between 333,000 - 550,000 kg/yr of pelagics (mainly dolphinfish) (Rodriquez-Ferrer and Rodriquez-Ferrer 2014). In the eastern Caribbean Sea, while dolphinfish is considered the most important pelagic fish landed by commercial fishers, many island nations do not report their recreational landings (only commercial for some), thereby underestimating the total harvest of this species in the region (Parker 2006). In fact, Mahon (1999) stated only 8 of the 34 states in the western central Atlantic reported dolphinfish landings to the Food and Agriculture Organization (FAO), and while commercial landings have appeared to level off in recent years, recreational landings appear to still be on the increase (SAFMC 2003). Therefore, the lack of information on the amount of dolphinfish landed should be a matter of urgent concern to all countries that exploit this species in the western central Atlantic, especially given that dolphinfish throughout the region represent one population (Merten 2014d).

Currently, in the western central Atlantic, there is no integrated regional fisheries management plan (FMP) for dolphinfish (Parker 2006), despite the access of more than 34 countries to the resource in the region. In the U.S., the South Atlantic Fisheries Council in conjunction with the Mid-Atlantic and New England Fisheries Councils established a FMP with the following federal management actions:

i) Limits on the commercial and recreational catch of dolphinfish (recreational= 60 fish/boat or 10 fish/person; commercial: managed through annual catch limits (ACL)),
ii) 50-cm fork length minimum size for dolphin off the east coast of Florida, Georgia, and South Carolina,
iii) Gear restrictions (hook and line / spearfishing gear only; cannot use longline in areas where prohibited for highly migratory species),
iv) Mandatory permits for recreational and commercial vessels, and
v) Use of sea turtle by-catch prevention measures (SAFMC 2004). While these management measures are beneficial

for dolphinfish conservation within U.S. south Atlantic federal waters, because the actions are not implemented by all states and nations landing dolphinfish in the western central Atlantic, it would be an unwise assumption to think that unmanaged and unregulated fishing practices are unable to adversely affect this species when fishing pressure is increasing each year, even despite the species high fecundity and growth rate (Oxenford 1999).

Recently, in the western central Atlantic, conventional mark and recapture data showed a northern seasonal progression (south to north) in dolphinfish movements along the U.S. east coast, movements away from the coast were initiated in the south and mid-Atlantic Bights (Merten et al. 2014a), and dolphinfish appear to make annual circuits through the Sargasso Sea to the northern Caribbean Island nations and The Bahamas. From these studies it is obvious that there is exchange of dolphinfish between the U.S. east coast and The Bahamas, but what is not firmly established is the temporal and spatial connection of dolphinfish exchange between Caribbean Island nations, The Bahamas, and the U.S.; this information is necessary to prioritize the implementation of widespread management actions to conserve and sustain the dolphinfish population in the western central Atlantic.

In this paper, the horizontal movements of dolphinfish within the northeastern Caribbean Sea are investigated using conventional and pop-up satellite tagging data from 2008 - 2013. The main objectives were to:

i) Quantify intra and inter-regional dispersal movements,
ii) Differentiate north (tropical Atlantic) and south (Caribbean Sea) movement rates and trajectories, and
iii) Draw comparisons from surface drifter tracks monitored in the region.

From the results, variation in movements relative to the U.S., The Bahamas, Greater Antilles, and northern Lesser Antilles, regional oceanography, and a seasonal return migration towards the Yucatan Channel/Loop Current and the Straits of Florida/Gulf Stream are assessed.

METHODS

Horizontal Movements: Conventional and Single-Point Pop-up Satellite Data

Conventional dolphinfish mark (n = 540; 33.02 - 130.5 cm FL; 70.52 ± 15.21 cm FL) and recapture (n = 22; 108.8 - 130.8 cm FL; 120.55 ± 9.66 cm FL) and pop-up satellite tagging data (n = 6; 107.5 and 120 cm FL) relative to the northeastern Caribbean Sea were provided by the Dolphinfish Research Program (DRP) from 2008 until 2014. Release and recapture data were analyzed following Merten et al. (2014b).

Non-geolocating high-rate X-tag pop-up satellite archival transmitters (PSATs)(L-31.11 cm; W-40 g) were used in this study (Microwave Telemetry Inc., Columbia, MD, USA). Only fish that transmitted data (n = 3) were analyzed (ID 113350 Female; ID 126828 male; ID 126830 male), but all transmitters were programed for 30 day deployments. From these deployments, only the release and pop-up locations were used to show linear displacements; the pop-up locations were estimated by Argos© using the least squares analysis algorithm. Fish selection and methodology for tagging followed methods used in Merten et al. (2014c).

Spatial Analysis

Straight-line distances were calculated between all release and recapture events using ArcGIS 10.0 and movements were classified into three categories:

i) Intra-regional
ii) Emigration movements between the tropical Atlantic and Caribbean Sea, and
iii) Immigration to the northeastern Caribbean Sea (Puerto Rico; U.S.V.Is.; B.V.Is; Anguilla; St. Kitts and Nevis; Antigua and Barbuda).

Release locations were analyzed relative to the 200-m isobath which was used to represent the shelf edge in the northeastern Caribbean Sea and movement headings were examined relative to straight-line distances between mark and recapture locations. Spatial data for the shoreline and isobaths were obtained from the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NGDC) [http://www.ngdc.noaa.gov/mgg/shorelines/data/gshhs/] and North American Cartographic Information Society [http://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-bathymetry/], respectively. Lastly, spatial movements were compared to movements of surface drifters obtained from NOAA's Atlantic Oceanographic and Meteorological Laboratory [http://www.aoml.noaa.gov/envids/glddirkrigparttrk_spatial_temporal.php].

Data Analysis

To test if dolphinfish movements were different from general current flow, comparisons were made between tagging results and movements of surface drifters (n = 196) following methods developed in Merten et al. (2014b). Here, surface drifters at liberty from January 1, 2002 until June 30, 2013 in an area encompassing the northeastern Caribbean Sea (20°N x 69°W x 16.5°N x 59°W) were examined. Furthermore, while dolphinfish are present in the region year-round, temporal variation in arrival time of large dolphinfish does occur. Seasonally, larger size classes (> 90 cm FL) arrive first to the tropical Atlantic (north of Puerto Rico, the U.S.V.I.s, and B.V.I.s; October - February) then to the Caribbean Sea (south of Puerto Rico, the U.S.V.I.s, and B.V.I.s; December - May)(Oxenford and Hunte 1986). As a result, drifters were filtered according to season and location to compare seasonal surface current movements to dolphinfish movements. For fish released in the region, the majority of the releases (89.8%) and recoveries (80.0%) occurred earlier in the tropical Atlantic (November-January) than in the Caribbean Sea (February - May; 51.0% released; 100% recovered). Therefore, drifters were then filtered to only those that originated in the tropical Atlantic (20°N x 64.5°W x 18.3°N x 59°W) or the

Caribbean Sea (16.5°N x 64.5°W x 18.3°N x 59°W) between November to January, and February to May, respectively. Lastly, the Mona and Anegada Passages between Hispaniola and Puerto Rico, and the Virgin Islands and Saba Bank (20°N x 64.5°W x 17.5°N x 59°W), respectively, has a predominant southward flow into the Caribbean Sea (Johns et al. 1999). Hence, movements of surface drifter tracks (i.e., continue west to the north of the Virgin Islands in the tropical Atlantic, or drift south through the passages and enter the Caribbean Sea) were investigated to highlight where dolphinfish may take a westward movement route to the north (originating and moving west north of 18.2°N) or south (originating and moving west south of 18.2°N) of the Greater Antilles. Based on these criteria, surface drifters were categorized as:

i) Westward movements to the north of the Greater Antilles in the tropical Atlantic (n = 78),
ii) Westward movements to the south of the Greater Antilles in the Caribbean Sea (n = 41),
iii) Moving from north to south via the Mona or Anegada Passages then west in the Caribbean Sea (n = 22), and
iv) South to north via the Mona or Anegada Passages then west in the tropical Atlantic (n = 55).

RESULTS

From 2008 to 2014 there were 13 dolphinfish movements relative to the northeastern Caribbean Sea. These movements ranged between 231 and 557 DAL (days at liberty). Overall, dolphinfish release locations in the northeastern Caribbean Sea (n = 248) were on average 23.26 ± 14.22 km and 16.32 ± 14.72 km from shore and the 200-m isobath, respectively (Figure 1). Dolphinfish released around Puerto Rico, where the tagging effort was the strongest, averaged 26.34 ± 14.50 km and 19.54 ± 15.09 km off the north coast, and 19.71± 9.56 km and 12.51± 10.35 km off the south coast. Of all dolphinfish tagged, only 20 (3.6%) were released landward (maximum 5.75 km inside) of the 200-m isobath; many of those (n = 8) occurred east of San Juan. The median distance dolphinfish were released from shore was 20.32 km with the maximum distance being 82.49 km; 75% (n = 185) of the dolphinfish release locations were within 30 km from shore.

Movements Obtained with PDTs and PSATs

There have been seven dolphinfish recaptures reported in Hispaniola, the Bahamas, or the U.S. east coast (Figure 2). All of these fish were released off of San Juan, Puerto Rico. In the Caribbean Sea, three movements (14%) were observed to Hispaniola after being released off of La Parguera, PR (Figure 2). Dolphinfish movements to the northeastern Caribbean Sea consisted of six recaptures (Figure 2). Of these, three were recaptured off La Parguera, Puerto Rico, within 13 - 35 km of each other; two occurred in the same month but during different years. The other recaptures occurred in the northern Lesser Antilles. Overall, all recaptures occurred within 7 to 11 months after being released along the U.S. east coast; one fish was recaptured after 18 months after being released off of Miami, Florida. All fish recaptured except one were released along the eastern Florida shelf. The other was released off Charleston, South Carolina.

Directionality

Regional headings were predominately westerly (274.42° ± 21.07°) and were not significantly different between the tropical Atlantic (n = 10) and Caribbean Sea (n = 7) (Mann-Whitney; $p = 0.386$)(n = 17). For fish released and recaptured off the north coast of Puerto Rico, the majority of the headings were towards the west-northwest or northwest (50%; n = 5), while one was towards the west and the rest were towards the west-southwest (n = 4). Off the south coast, half of the fish recaptured moved westward and west-southwestward. All recapture events, regardless of being released in the tropical Atlantic or Caribbean Sea, occurred to the west, consistent with overall surface drifter movements (Figure 3).

Seasonality

Tagging effort within the northeastern Caribbean Sea varied by location. In the northern Lesser Antilles (Antigua), dolphinfish were tagged and released (n = 35) in every month throughout the year except February and March. The majority of the fish, however, were released from June - August (68%; n = 24). In the northeastern Greater Antilles, fish released south of St. Johns (n = 7), United States Virgin Islands, in the Anegada Passage, were released in February (n = 1), April (n = 2), August (n = 3), and December (n = 1). Off Puerto Rico, tagging effort was focused along the north (n = 396; 78.5%) and south coast (n = 103; 20.4%) and in the Mona Passage (n = 5; 1.0%). Along the north coast, both releases and recoveries were greatest from October-January (n = 374: 94.4%; n = 8: 83.3%), while off the south coast releases and recoveries were greatest from February to May (n = 53; 51.4%; n = 4; 100%). In the Mona Passage, only five dolphinfish were released between October (n = 2) and March (n = 3) and none were reported as recovered; however, two recoveries occurred in the Mona Passage from fish released off of San Juan, Puerto Rico, and south of St. Johns, USVI, during April (released in January) and June (released in February), respectively.

DISCUSSION

While dolphinfish recaptures within the northeastern Caribbean Sea only constituted 5% of all recaptures recorded (Merten et al. 2014b) in the western North Atlantic since 2002, these recoveries identified specific movement patterns influenced by regional oceanography and island geomorphology, and further establish that a regional approach to management of this species is necessary.

Regional exchange of dolphinfish occurred between Puerto Rico and the Dominican Republic, The Bahamas, and the U.S. east coast; in the Caribbean Sea exchange occurred between Puerto Rico and the Dominican Republic. It is important to note that more fish should be conventionally tagged and released, particularly in the Caribbean Sea south of Puerto Rico, the USVIs, and in the northern Lesser Antilles, to establish exchange with other

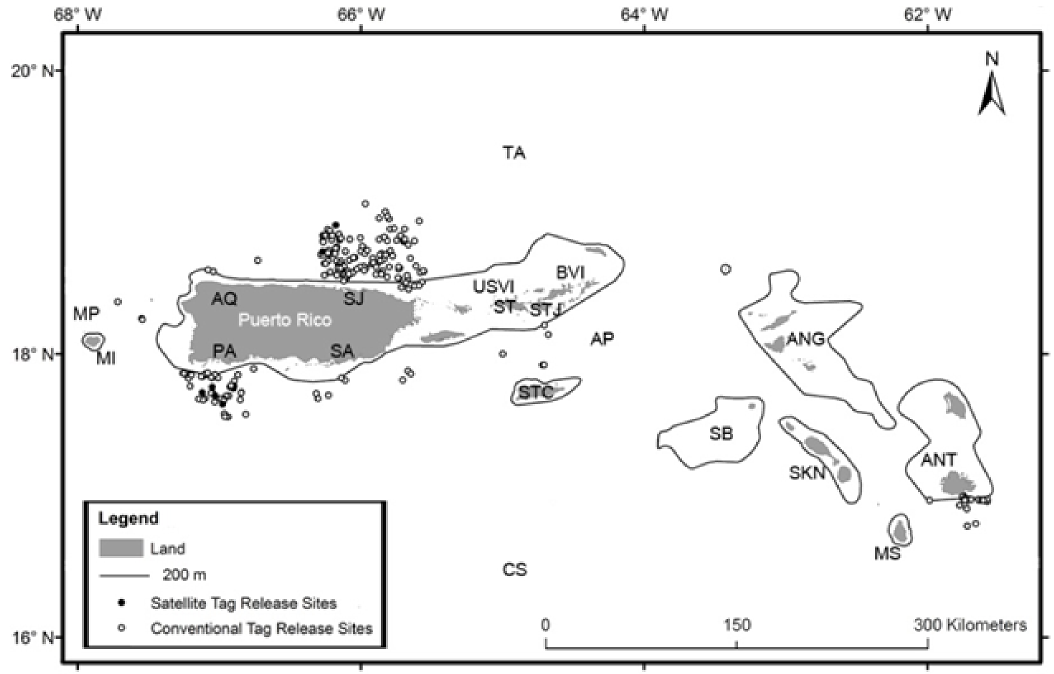

Figure 1. Conventional (white ovals) and satellite (black ovals) mark and release locations for dolphinfish released in the northeastern Caribbean Sea since January 1st, 2008. Puerto Rico: PR; SJ: San Juan, PR; Salinas, PR: SA; PA: La Parguera, PR; Aquadilla, PR: AQ; USVI: United States Virgin Islands; St. Thomas, USVI; STJ: St. John, USVI; STC: St. Croix, USVI; BVI: British Virgin Islands; AP: Anegada Passage; TA: Tropical Atlantic; CS: Caribbean Sea; MP: Mona Passage; MI: Mona Island; SB: Saba Bank; ANG: Anguilla; SKN: St. Kitts and Nevis; ANT: Antigua; MS: Montserrat.

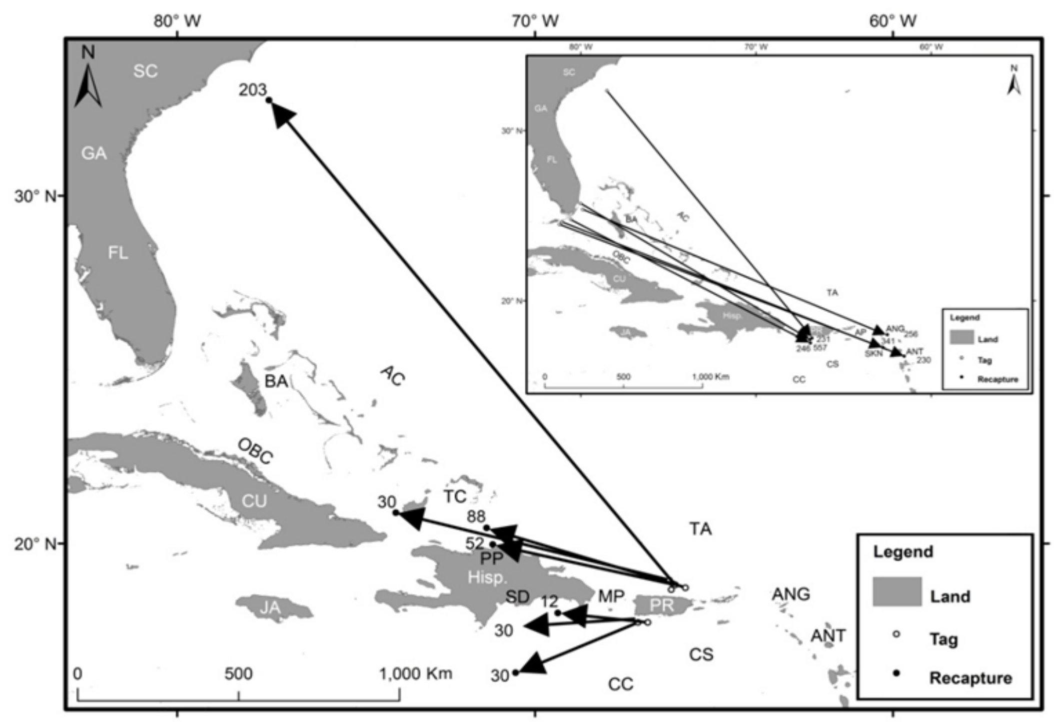

Figure 2. Movements of dolphinfish to and from the northeastern Caribbean Sea. Numbers indicate days at liberty (DAL) for each recapture. TA: Tropical Atlantic; CS: Caribbean Sea; AP: Anegada Passage; Puerto Rico: PR; Hispaniola: Hisp.; Jamaica: JA; Cuba: CU; The Bahamas: BA; Florida: FL; Georgia: GA; South Carolina: SC; Caribbean Current: CC; Tropical Atlantic: TA; Anguilla: ANG; St. Kitts and Nevis: SKN; Antigua and Barbuda: ANT; Old Bahamas Channel: OBC; Antilles Current: AC.

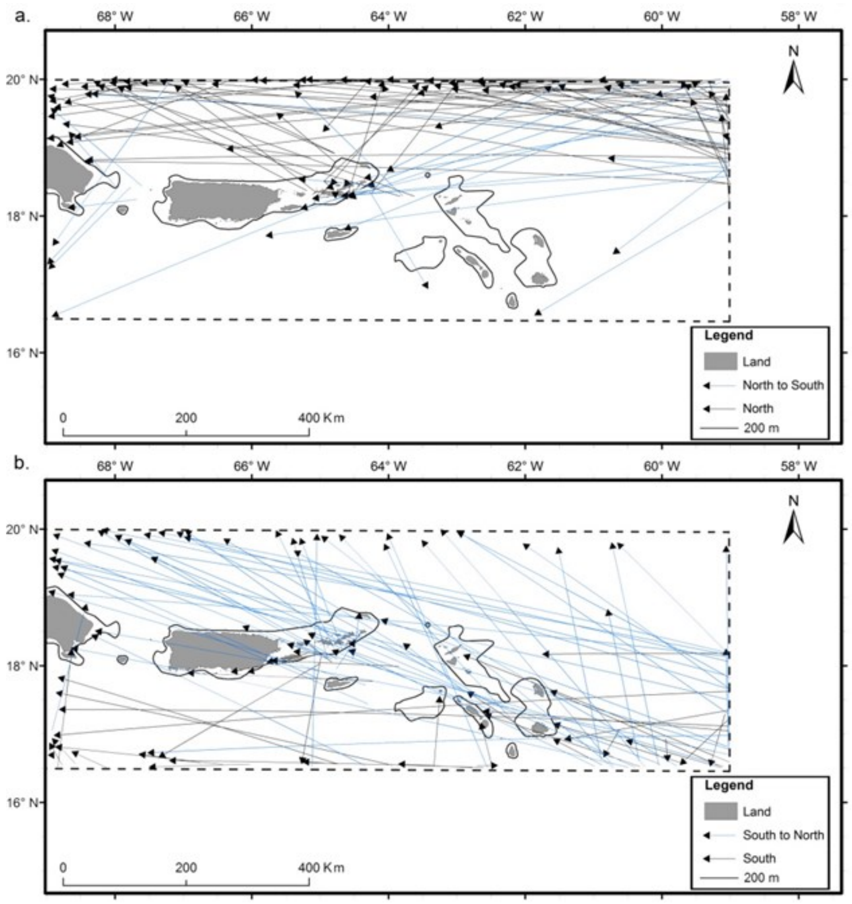

Figure 3. Straight-line surface drifter tracks in the northeastern Caribbean Sea from January 1st, 2002, to June 30th, 2013. The dashed line indicates the region of interest where the upper panel (a.) depicts drifters that originated and moved west north of 18.2°N (North) and originated north of 18.2°N and moved west south of 18.2°N (North to South); the lower panel (b.) shows drifters that originated and moved west south of 18.2°N (South) and originated south of 18.2°N and moved west north of 18.2°N (South to North).

Caribbean nations such as Jamaica, the Cayman Islands, Mexico, and regions such as the Gulf of Mexico and Straits of Florida. This information would allow more robust estimations of stock dynamics (seasonal abundance and recruitment) and aid in providing predictive information on the timing of movement of fish between EEZs throughout the Caribbean Sea and Gulf of Mexico.

Conventional straight-line movements in the tropical Atlantic indicated that dispersal headings were towards the west and northwest; in the Caribbean Sea, dispersal headings were towards the west and southwest. Although conventional straight-line movements are not reflective of the precise routes the fish took to their respective recapture locations, the westerly movement trajectories are likely reflective of the response of regional oceanography to broad-scale meteorological features in the northeastern Caribbean Sea. For dolphinfish, there are likely three emigration routes from the northeastern Caribbean Sea:

i) Northwest along the Greater Antilles in the tropical Atlantic,
ii) Southwest along the Greater Antilles in the Caribbean Sea then northwest towards the Yucatan Channel, and
iii) Latitudinal interchange of fish between the tropical Atlantic and Caribbean Sea via the Mona Passage.

In the tropical Atlantic, the generally wind-driven northward flowing Antilles Current (Lee et al. 1996) is largely influenced by the Intra-Americas Sea low-level atmospheric jet (IALLJ), a strong tradewind current of considerable east-west extent centered over the Caribbean Sea (Amador, 2008), which directs surface water from the tropical Atlantic towards the Gulf Stream (Johns et al. 1999). In the Caribbean Sea, the Caribbean Current reacts to the North Brazil Current retroflection (Corredor and Morell, 2001) and meridional overturning circulation (Johns et al. 2002), and is responsible for significant volume transport coming through the Windward (south to north; Grenada, St. Vincent, and St. Lucia Passages) and Leeward Island Passages (south to north; Dominica, Guadeloupe, Antigua, and Anegada Passages)(Johns et al. 2002) directed towards the Yucatan Channel and Loop Current (Lin, 2010), which eventually leads into the Straits of Florida and the Gulf Stream (Johns et al. 1999). These marine and atmospheric features appear to drive dolphinfish in the northeastern Caribbean Sea towards the Straits of Florida and beginning of the Gulf Stream via the Old Bahamas Channel (north of Cuba) or Bahamian escarpment (northeast of The Bahamas) or towards the Loop Current and Straits of Florida via the Yucatan Channel (western Caribbean Sea).

Recaptures within the Mona Passage originated in both the tropical Atlantic and the Caribbean Sea, examples that suggest emigration of dolphinfish from the north or the south. While studies have shown that the overall trend of volume transport in the Mona Passage is to the south (Johns et al. 1999, John et al. 2002), surface drifter paths suggest surface currents are not uni-directional and can move in both directions. Because the Mona Passage is considerably deep (~400 m sill depth) (Johns et al. 2002) compared to the observed vertical extent of dolphinfish in the region (155 m tropical Atlantic; 112 m in the Caribbean Sea; W. Merten University of Puerto Rico, unpublished), volume transport should not be construed as the sole factor influencing dolphinfish movements through the passage. Morelock et al. (2001) suggest that movements of surface currents above the mixed layer are strongly influenced by semi-diurnal tides, which tend to rotate clockwise, and peak at 50 - 75 cm/sec. Approximately in phase with the tides in the Mona Passage, are internal waves that have been observed to develop and propagate into the Caribbean Sea at a site northeast of Mona Island called “el Pichincho,” a submerged ridge (minimum depth ~125 m) that extends across the middle of the passage from Hispaniola towards Puerto Rico (Corredor et al. 2008). Internal waves, centered at around 100 m at this site, have been measured to span a vertical range of 50 m, and are thought to influence the aggregation of pelagic fish (marlin, tuna, dolphinfish) due to the oscillatory nature of the waves entraining phytoplankton and zooplankton between the surface mixed layer and deeper bottom waters (Morell et al. 1995). While the vertical extent of dolphinfish has not been investigated in the Mona Passage, a study did find that dolphinfish do appear to partake in surface (0 - 30 m) and at-depth (> 30) feeding strategies in the western central Atlantic (Merten et al. 2014c) which suggests that dolphinfish could feed relative to the productive interfaces associated with these features in the Mona Passage. Dolphinfish in this study, were in fact tagged and released, and recaptured, in the proximity of “el Pichincho,” which confirms that dolphinfish occur in the passage, and hence could be influenced by these processes. However, the results presented here are inconclusive as to how dolphinfish may move, both horizontally and vertically, when they enter the Mona Passage from the tropical Atlantic or Caribbean Sea. Future studies should investigate both the short-term (< 2 days) vertical movement extent of dolphinfish relative to internal waves and bathymetric features in the passage, and emigration movements, using active tracking pop-up archival transmitters.

From the U.S. east coast, six dolphinfish entered the northeastern Caribbean Sea. In a previous study, Merten et al. (2014b) documented a recirculation trend, ranging from 2 - 318 days, for dolphinfish immigration to the Bahamas and Greater Antilles Islands (Dominican Republic and Cuba) from Florida. Based on comparisons of dolphinfish movements, surface drifter tracks, and emigration from the U.S. east coast (Merten et al. 2014a), they concluded that dolphinfish appear to make circuits around the western central Atlantic which vary widely in temporal and spatial scale and are dependent on where fish exit the U.S. east coast and head into the north central Atlantic. Interestingly, blue marlin released off of North Carolina and the Bahamas were recaptured 412 and 315 days later off of St. Thomas and Barbados, respectively (Witzell and Scott, 1990). The recaptures recorded in this study, and the movements observed for blue marlin, support this same trend, but represent a larger circuit (231 - 557 days) than observed to the Bahamas, for dolphinfish immigrating to the northeastern Caribbean Sea.

Dolphinfish were observed to be seasonally abundant in the northeastern Caribbean Sea. In the tropical Atlantic peak abundances and size classes run from October to February, while in the Caribbean Sea the timing is from December to May. Recently, a genetic analysis of the population structure of dolphinfish relative to Puerto Rico concluded that dolphinfish that occur around the island throughout the year represent one population (Merten 2014); therefore, differences in seasonal abundance between the north and south coast of Puerto Rico are not due to movements of different stocks of dolphinfish but rather different movement routes. The immigration movements recorded here highlight two of the Leeward Island Passages (north to south; Anegada and Antigua) as the corridors for movement: in the Anegada Passage, the flow is predominately southward into the Caribbean, with the most intense flow found at the west side of the passage near the Virgin Islands (Johns et al. 1999); the Antigua Passage is much smaller in scale, but estimates do suggest volume transport to the eastern Caribbean Sea of 2.1 Svendrups (1 Sv = 10^6 m^3/s)(Johns et al. 2002). Given the locations of the recaptures, it is likely that dolphinfish used these corridors to move into the northern Lesser Antilles and Caribbean Sea.

The recaptures recorded in the northern Lesser Antilles and Caribbean Sea (Figure 2) occurred from December - May, which coincides with the peak abundance and size of dolphinfish based on anecdotal reports from fishermen in the region; fishermen suggested that dolphinfish were absent when “green water” was present in the Caribbean Sea. In the Caribbean Sea, “green water” is low-salinity, phytoplankton and colored dissolved organic matter (CDOM) rich water, associated with Orinoco River Plume (ORP) mesoscale eddies that spiral westward across the basin from August to November, 3 to 4 months after the peak in runoff through the Orinoco and Amazon river deltas (Corredor and Morell 2001, Corredor et al. 2004). These vortices are thought to originate as North Brazil Current Rings, generated by fluxes in the North Brazil Current Retroflection (Johns et al. 1990); despite their size, they enter the Caribbean Sea with little loss in mass and momentum through the Windward Island Passages, where interaction with Trinidad and Tobago is thought to induce cyclonic (counter-clockwise) or anti-cyclonic (clockwise) rotation (Carton and Chao 1999). As they propagate westward, these features cause shoaling of the deep chlorophyll maximum (DCM) layer which enhances primary productivity by bringing nutrient rich waters into the euphotic zone (Corredor et al. 2004), as a result they diminish the transparency of the typically blue oceanic waters. While dolphinfish feed during day and night, studies have found that they are primarily visual predators (Massutí et al. 1998, Olson and Galván-Magaña 2001), an attribute which would be useless in waters with reduced visibility. In this study, the majority of releases in the Caribbean Sea occurred from February to May, but small fish (< 82 cm FL) were released during June (n = 7), July (n = 8), August (n = 3), September (n = 3), and October (n = 12) of 2011 and 2012, a time when green water did not seem to be present. While the influence of the ORP on the variability of the Caribbean Current has been well documented (Chérubin and Richardson 2006), the biological response of Caribbean fisheries to the freshwater influx, and the seasonal and interannual northern extent of the plume to the northeastern Caribbean Sea, is still largely unknown (Cowen et al. 2003).

Until recently, few studies have described the differential patterns of dolphinfish movements throughout the western central Atlantic. The present study adds to the growing knowledge of their annual Atlantic migration, and provides the underpinnings for variability in their return migration towards the Yucatan Channel/Loop Current or Straits of Florida/Gulf Stream from the tropical Atlantic, and Caribbean Sea, respectively. The results of the present study suggest that fishing mortality could be higher in the tropical Atlantic than in the Caribbean Sea, due to the propensity for dolphinfish to move more slowly in those waters. What remains unknown, however, is how dolphinfish within the Caribbean Sea seasonally respond to ORP mesoscale eddies, internal waves and current dynamics in the major Antillean Passages (i.e., Windward and Leeward Island Passages, and Greater Antilles Passages), variability of the speed and extent of the Caribbean Current, and if they follow the Caribbean Current into the Gulf of Mexico. Future studies should deploy both short (< 2 days) and long-term (> 90 day) pop-up archival (actively tracked) and satellite pop-up archival (passively geo-located) transmitters to begin to describe how dolphinfish may respond to changes in regional oceanography and the exact dispersal and immigration routes they take towards the west.

The results reiterate exchanges between fisheries of Caribbean Island nations, The Bahamas, and the U.S., information that should be used to implement an integrated fishery management plan with regionally consistent management measures such as a minimum size and bag limit due to increasing fishing pressure between jurisdictions in the region (Parker et al. 2006). This recommendation is based on both genetic studies that have shown that dolphinfish being targeted by Caribbean or U.S. based fisherman are harvesting the same population (Díaz-Jaimes et al. 2010, Merten 2014) and increasing evidence from movement studies that dolphinfish are regionally connected in an annual western central Atlantic migration circuit (Merten et al. 2014a, Merten et al. 2014b). However, this raises the question for future studies to investigate the notion of sequential connectivity of good years/high abundance versus bag years/low abundance between geographically separated EEZs and whether there is a predictive signal based on oceanographic/meteorological processes (e.g., IALLJ response to ENSO, Gulf Stream response to NAO, dynamics of the ORP) supplying additional habitat or conditions (*Sargassum* spp., heightened frontal boundaries, better larval dispersal) that will favor increased recruitment. Based on these results specific management measures should be taken to ensure future stock sustainability (Table 1).

Table 1. Specific management recommendations for both recreational and commercial fisheries sectors based on analysis of movement and genetic data for dolphinfish in the western central Atlantic (WCA). U.S.: United States; NE C.S.: northeastern Caribbean Sea; TAC: total allowable catch.

Movement or Genetic Attribute	Specific Management Recommendation
Annual return migrants from U.S. to NE C.S. to U.S.	Expand 50 cm FL minimum size to NE C.S.
Biomass exchange between multiple jurisdictions	Enhance effectiveness of monitoring and recording accurate catch data
Seasonal jurisdictional replenishment	Allocation based on member state recreational or commercial status
Highly migratory	Determine TAC jointly among all jurisdictions that land dolphinfish
Moderate gene flow	WCA stock assessments should use single stock approach

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LITERATURE CITED

Amador, J.A. 2008. The Intra-Americas Sea low-level jet: Overview and future research. *Trends and Directions in Climate Research* **1146**: 153-188. Doi:10.1196/annals.1446.012.

Carton, J.A. and Y.Chao. 1999. Caribbean Sea eddies inferred from TOPEX/POSEIDON altimetry and a 1/6° Atlantic Ocean simulation. *Journal of Geophysical Research* **104**:7743-7752.

Chérubin, L.M. and P.L. Richardson. 2007. Caribbean current variability and the influence of the Amazon and Orinoco freshwater plumes. *Deep-Sea Research* Doi:10.1016/j.dsr.2007.04.021

Corredor, J.E. and J.M. Morell. 2001. Seasonal variation of physical and biogeochemical features in eastern Caribbean surface water. *Journal of Geophysical Research* **106**: 4517-4525.

Corredor, J.E., J.M. Morell, J.M., Lopez, J.E., Capella, and R.A. Armstrong. 2004. Cyclonic eddy entrains Orinoco river plume in eastern Caribbean. *EOS* **85**:197, 201-202.

Corredor, J.E., J.M. Morell, J.E., Capella, S. Glenn, and D. Pabst. 2008. Internal tides in the Mona Passage. American Geophysical Union, Spring Meeting 2008. Available online at: http://adsabs.harvard.edu//abs/2008AGUSMOS33B..01C. (August 2014)

Corredor, J.E. 2008. Development and propagation of internal waves in the Mona Passage. *Sea Technology* October:48-50.

Cowen R.K., S. Sponaugle, C.B. Paris, J.L. Fortuna, K.M.M. Lwiza, and S. Dorsey. 2003. Impact of North Brazil Current rings on local circulation and coral reef fish recruitment to Barbados, West Indies. Pages 443-462 in: G.J. Goñi (ed.) Interhemispheric Water Exchange. Elsevier, Waltham, Massachusetts USA.

Díaz-Jaimes P., M. Uribe-Alcocer, A. Rocha-Olivares, F.J. García-de-León, P. Nortmoon, and J.D. Durand. 2010. Global phylogeography of the dolphinfish (*Coryphaena hippurus*): the influence of large effective population size and recent dispersal on the divergence of a marine pelagic cosmopolitan species. *Molecular Phylogenetic Evolution* **57**:1209–1218. doi: 10.1016/j.ympev.2010.10.005

Johns, W.E., T.N. Lee, F.A. Schott, R.J. Zantopp, and R.H. Evans. 1990. The North Brazil Current retroflection: Seasonal structure and eddy variability. *Journal of Geophysical Research: Oceans 1978-2012.* **95**:22103–22120.

Johns, W.E., D.W. Wilson, and R.L. Molinari. 1999. Direct observations of velocity and transport in the passages between the Intra-Americas Seas and the Atlantic Ocean, 1984-1996. *Journal of Geophysical Research* **104**: 2585-2582.

Johns, W.E., T.L. Townsend, D.M. Fratantoni, and W.D. Wilson. 2002. On the Atlantic inflow to the Caribbean Sea. *Deep-Sea Research* **49**:211-243.

Lee, T.N., J. Yoder, and L. Atkinson. 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf. *Journal of Geophysical Research* **96**:22191–22205.

Lin, Y. 2010. *Circulation and Associated Variability in the Intra-Americas Sea: The Role of Loop Current Intrusion and Caribbean Eddies.* Ph.D. dissertation. Dalhousie University, Halifax, Nova Scotia, Canada. 154 pp.

Merten, W., R. Appeldoorn, and D. Hammond. 2014a. Movements of dolphinfish (*Coryphaena hippurus*) along the U.S. east coast as determined through mark and recapture data. *Fisheries Research* **151**:114-121. http://dx.doi.org/10.1016/j.fishres.2013.10.021.

Merten, W., R. Appeldoorn, and D. Hammond. 2014b. Spatial differentiation of dolphinfish (*Coryphaena hippurus*) movements relative to the Bahamian archipelago. *Bulletin of Marine Science* **90**. doi:10.5343/bms.2013.1078.

Merten, W., R. Rivera, R. Appeldoorn, and D. Hammond. 2014c. Diel vertical movements of adult male dolphinfish (*Coryphaena hippurus*) in the western central Atlantic as determined by use of pop-up satellite archival transmitters. *Marine Biology* **161**:1823-1834. doi:10.1007/s00227-014-2464-0 .

Merten, W. 2014d. *Dolphinfish Horizontal and Vertical Movements and Population Structure in the Western Central Atlantic.* Ph.D. dissertation, University of Puerto Rico, Mayagüez, Puerto Rico. 146 pp.

Morell, J.M., J.E. Corredor, J.E. Capella, and J. Lopez. 1995. Density structure oscillations at "El Pichincho": possible implications on pelagic fisheries. Invited speaker to the AGU Chapman Series Conferences: Circulation in the Intra-Americas Sea, January 22-26, 1995, La Parguera, Puerto Rico.

Morell, J.M., J.E. Corredor, and W.J. Merryfield. 2006. Thermohaline staircases in a Caribbean eddy and mechanisms for staircase formation. *Deep-Sea Research II* **53**:128-139.

Morelock, J., J. Capella, J.R. Garcia, and M. Barreto. 2000. PUERTO RICO - Seas at the Millennium. In: C. R. C. Sheppard (ed.) *Seas at the Millennium*. Oxford Press, London, England.

Olson, D.B., F.A. Schott, R.J. Zantopp, and K.D. Leaman. 1984. The mean circulation east of the Bahamas as determined from a recent measurement program and historical XBT data. *Journal of Physical Oceanography* **14**:1470-1487.

Parker, C.K., K. Kleisner, and J. Sladek-Nowlis. 2006. Preliminary assessment of the western central Atlantic dolphinfish (*Coryphaena hippurus*) Stock: A Caribbean regional fisheries mechanism project. Sustainable Fisheries Division Contribution No. SFD-2006-041. Department of Commerce/National Oceanic and Atmospheric Administration/Southeast Fisheries Science Center, Miami, Florida USA. 13 pp.

SAFMC. 2004 Fishery management plan for the dolphin and wahoo fishery of the Atlantic. South Atlantic Fisheries Management Council, Charleston, South Carolina USA.

Witzel, W. and E. Scott. 1990. Blue marlin, *Makaira nigricans*, movements in the western North Atlantic Ocean: Results of a cooperative game fish tagging program, 1954-88. *Marine Fisheries Review* **52**:12-17.