Movement Patterns of Atlantic Tarpon *(Megalops atlanticus*) in Brewers Bay, St. Thomas US Virgin Islands

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Telemetry case report

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Abstract

Background

Atlantic tarpon (*Megalops atlanticus*) are highly migratory species ranging along continental and insular coastlines of the Atlantic Ocean. Despite broad geographic distribution and importance as recreational fisheries, little is known about space-use patterns of tarpon within the Eastern Caribbean. Acoustic telemetry was used to track tarpon (n=14, 61-95cm-FL) from September 2015 to February 2018 in St. Thomas, U.S. Virgin Islands to understand horizontal and vertical movements during diel, crepuscular and seasonal periods and under different environmental conditions.

Results

Eight tarpon were transient while four had >80% residency and average activity space of 0.76 km^2 (range = 0.075-1.174 km^2) within a small (~1.8km^2) bay. Tarpon occurred in <18 m depth with occasional movements to deeper water, including during hurricanes. Activity was greater during day compared to night, with peaks during crepuscular periods. During the day tarpon primarily utilized the waters along the St. Thomas airport and at night tarpon typically remained in a small shallow lagoon. However, when temperatures in the lagoon exceeded 30 °C, tarpon moved to cooler, deeper waters outside the lagoon.

Conclusion

This study showed distinct and mostly non-overlapping home ranges except when seasonally abundant food sources were present and provided a unique perspective on the effects of extreme environmental conditions on tarpon movement and habitat use. These metrics are useful for management of tarpon, particularly under changing climatic conditions.

Background

Animal movement is a fundamental ecological process used to identify habitat use, community structure, biodiversity patterns, trophic interactions, reproductive behavior, and population distribution and abundance [1–4]. Knowledge of these outcomes can be beneficial for selection of ecologically relevant spatial and temporal scales for management [5]. Movement and space-use in the aquatic environment is a multi-dimensional process [6–10]. Consequently, measuring changes in horizontal and vertical dimensions at different temporal scales (e.g., day, night, crepuscular periods, seasonal, etc.) can provide insights into habitat use, intra- or inter-specific interactions, behavioral responses to thermal or chemical stratification, and physiological impacts, among others [6, 9].

Fish utilize different temporal and spatial scales to find food, reproduce, avoid predators or seek favorable environmental conditions; with some larger species (e.g., sharks, marlin, tuna and tarpon) moving between winter and summer sites [2, 6, 10, 11]. Migratory species can also exhibit high site fidelity to nearshore areas, where an individual fish occupies a geographically discrete home range or activity space where they partake in routine activities such as feeding, resting and breeding [1, 12–14]. For many highly mobile tropical marine fish, activity spaces can encompass multiple habitat types such as coral reefs, seagrass beds and mangroves habitats, as well as lagoons and estuaries [5, 15, 16].

Atlantic tarpon (*Megalops atlanticus*) is a highly mobile pelagic species that supports important fisheries. Tarpon range across coastal areas, estuaries, and rivers of the western and eastern Atlantic Ocean, the Caribbean Islands and the Gulf of Mexico [6, 17, 18]. Tarpon spend their leptocephali larval stage in open ocean and as juveniles settle nearshore in warm estuarine, mangrove and lagoon habitats, where food resources are high and predator pressure is low [16, 19–

21]. Adult tarpon typically range in size from 90–250 cm FL, with males reaching sexual maturity at 90 cm and females at 128 cm FL [17, 22–24]. Much of our knowledge of tarpon movements and behaviors come from satellite tracking and conventional anchor tag studies conducted in Florida, southeast Atlantic, Gulf of Mexico, and the northern Caribbean (e.g., Mexico, Belize, Cuba) [6, 17, 18, 25, 26]. These studies have focused on large-scale movements (> 500 km) of large adult tarpon (> 130 cm-FL). Little information exists on movements of tarpon within insular regions of the western Atlantic Ocean (i.e., the Lesser Antilles).

Acoustic telemetry is an effective technique for collecting direct and spatially explicit evidence of the small-scale three-dimensional movement patterns for fish. Target animals are implanted with a coded transmitter, typically in the body cavity, and released to be detected and recorded (location, depth, date, time) within an array of moored underwater acoustic receivers [5, 27–29]. Acoustic telemetry allows researchers to gather evidence on habitat utilization patterns, home range size, diel activity, site fidelity, migration pathways, ontogenetic habitat shifts, and vertical movements [27, 30]. In marine management, the data gained from acoustic telemetry studies have been used to design (size and placement) and evaluate effectiveness of marine protected areas [5, 28, 29], identify essential fish habitat [31] and assess the frequency of use within these areas [12, 13, 32].

This study applied acoustic telemetry to quantify the spatio-temporal movement patterns (i.e., activity space, depth gradients, rates of movement) of tarpon and the influence of changing environmental conditions in the U.S. Virgin Islands. This study addressed the following questions: a) what is the overall activity space of tarpon?; b) how does their activity space change during diel and crepuscular periods, as well as across months?; c) do tarpon show different rates of horizontal and vertical movement during different time scales (diel, monthly)?; d) how do changes in environmental conditions (i.e., water temperature, dissolve oxygen) influence activity space of tarpon?

Materials And Methods

Study site

Brewers Bay is located on the western end of St. Thomas, U.S. Virgin Islands (18° 20’ 28” N, 64°58’40” W) and is bounded by a commercial airport runway and small lagoon on the south, a sandy beach on the north-eastern shore and a rocky headland and smaller bay (Perseverance Bay) to the northwest (Fig. 1). Brewers Bay is 0.7 km^2 in area and ranges in depth between 0- 33.1 m (Fig. 1) with steep vertical slopes along the airport runway and around the rocky headland. The bay is composed of a variety of habitat types including sand, seagrass, patch reefs, fringing coral reefs, rocky reefs and rubble and reinforced concrete blocks (dolosse) around the seaward slopes of the airport runway. The lagoon is mostly soft muddy bottom with scattered rocks and dead corals. It is partly enclosed by the airport runway with the remaining shoreline composed of rocky reef or soft sediments and red mangrove trees (*Rhizophora mangle*).

Acoustic Array

The acoustic monitoring system consisted of an array of 45 omnidirectional receivers (VR2W, 69 kHz, Vemco Inc, Halifax, NS, Canada), moored and spaced equally across Brewers Bay, in the adjoining Perseverance Bay and along the seaward side of the airport runway. (Fig. 1). Range testing of receivers [33] across the study site was conducted over four days in June 2015, by placing receivers in depths ranging from 5 to 19 m and over different substrate types including shallow and deep coral/rock and seagrass/sand [34]. Probabilities of transmission were tested using three A69-1601 Vemco transmitters V9-2H (151dB), V13-1H (153dB) and V16-4H (158dB) that transmitted every 60 seconds. Transmitters were attached to mooring lines connected to cinder blocks and suspended 1 m above the bottom. A detection probability of 70% for V13-1H transmitters was selected providing high coverage throughout the study area with estimated detection ranges of 101 m in seagrass/sand and 120 m in coral/rock substrates (Fig. 1). Water temperature and dissolved oxygen (DO) were collected at several stations in Brewers Bay using Hobo temperature loggers and miniDot DO loggers that were attached to acoustic receiver moorings and recorded at 15-minute intervals (Fig. 1).

Fish capture

Atlantic tarpon (*M. atlanticus*) were caught using hook and line from a boat or dock between September 2015 and November 2016. Each fish (n = 14) was held upside-down in a floating cradle alongside the boat or dock and fork length (FL) and total length (TL) were measured to the nearest millimeter (mm). Acoustic transmitters (either V13 (13 mm x 36 mm; n = 8) or V13P (13 mm x 46 mm; n = 6) 69 kHz, Vemco Inc, Halifax, NS, Canada) were surgically implanted into the body cavity on the ventral side of the fish [35]. The V13P transmitters provided data on depth of fish. The incision was closed with surgical staples and treated with antibacterial ointment. After about 5 min of recovery, each fish was released at its capture location (Fig. 1).

Figure 1 Map of the Caribbean (A) and the island of St. Thomas in the U.S Virgin Islands (B) and study site in Brewers Bay (C) depicting bathymetry and the acoustic array with its station number and approximate range of 70% detection probability (circles). The detections ranges vary by habitat (deep hard bottom = 115 m, deep soft bottom = 120 m, shallow soft and hard bottom = 101 m) based on range testing [34]. Location of environmental data logger stations shown as green dots (temperature) and red diamonds (dissolved oxygen). Yellow dots represent approximate location where Atlantic tarpon were caught and released.

Data analyses

Detections were downloaded from receivers every three months and analyzed using R Version 3.4.3[36]. For each fish, the total number of detections, first/last day detected, number of days between first and last day, total days and residency index within Brewers Bay array were calculated. Residency Index is defined as the percentage of time spent within Brewers Bay and was calculated by dividing total days detected within the array by number of days between the first and last detection. Detections for each individual tarpon by receiver were plotted through time to investigate the presence of dropped tags, dead individuals, and short-term residency. This exploratory method was used to identify individuals with adequate data to conduct spatial home range analysis.

The center of activity (COA) location for resident fish (n = 4) was calculated every 30 minutes using mean position (latitude and longitude) of all detections during that time step [37]. Distance between COA relocation points and difference in time between each relocation point were calculated for each fish using 'adehabitatLT' package of R environment [38]. Calculated distances were divided by the time difference between each consecutive relocation point to compute rates of movement (ROM m/s).

Based on daily sunrise/sunset time charts for Charlotte Amalie, St. Thomas, USVI [39], crepuscular periods were bracketed between sunrise/sunset and astronomical twilight. Specifically, dawn was defined as -1 hr before Astronomical morning and + 1 hr after sunrise to account for seasonal changes in day length. Likewise, dusk was defined as -1 hr before Astronomical twilight to + 1 hr after sunset. Day and night periods were the remaining hours between bracketed dawn and dusk, respectively. These diel and crepuscular groupings were applied to COA detections, ROM calculations, depth-use, and activity space.

Home range spatial analyses

The COA position values were used to calculate activity space for individual fish by calculating minimum convex polygons (100% MCP) and kernel utilization distribution (50% and 95% KUD), respectively, using the 'move' and 'adehabitat' package in R environment [38, 40]. MCPs provided information on the extent of an individual's range or area used and included all outlying points that might be the result of exploratory movement or periodic migration not part of their typical activity. KUDs highlight the density of positions utilized within the activity space of an individual based on COAs, as well as estimated error around these positions [41, 42]. When necessary, a 'land' barrier polygon was used to clip out the area of MCP and KUD polygons that fell on land (rgeos package, [43]). The calculated MCP (100%) and KUD (50% and 95%) activity spaces were plotted in ArcGIS 10.6 for annual, diel/crepuscular, and monthly periods. To calculate the degree of activity space overlap among individuals (yearlong and in April only), a Home Range (HR) percent overlap analyses was applied using the 'kerneloverlaphr' function of the adehabitatHR package [38, 44, 45].

Statistical analyses

Repeated Measures Analyses of Variance (RM-ANOVA) was used to test for differences in KUD (50% & 95%) across monthly, diel and crepuscular periods, as well as monthly ROM. Individual tarpon were treated as random variables, and either monthly or diel/crepuscular periods were treated for autocorrelation effects (corAR1) using the 'lme' function of the nlme package for R [46, 47]. ANOVA and a Tukey *post hoc* test were used to test differences in rate of movement between diel/crepuscular periods. A 2-Way ANOVA tested differences in diel ROM across seasons. To assess relationship between monthly ROM and 50% KUD size, a linear regression was applied.

For tarpon with depth-enabled transmitters, depth measurements were binned into hourly and monthly periods and applied to boxplots to elucidate their vertical movement patterns. ANOVA and Tukey *post hoc* tested for differences in vertical movement across both diel/crepuscular and monthly periods. To assess relationship between daily average number of detections of tarpon and average temperature within the lagoon and waters along the airport runway a linear regression was applied for study period (September 2015-February 2018).

Results

Tarpon caught in Brewers Bay averaged 83.7 cm FL (range 61-95cm; Table 1). Of the 14 tarpon caught, 12 were successfully tagged with acoustic transmitters (2 of 14 tarpon shed their tag or died). Eight of 12 individuals (67%) were detected for less than a week and had fewer than 1000 detections and were thus considered transient and not included in further spatial analysis (Table 1). The remaining four tarpon (33%) were tracked for 32 to 472 days and had sufficient detections and duration to be considered resident to the area (residency index: 78% – 100%) (Table 1).

Activity space

The activity space of tarpon varied among individuals and through time. The average MCP for four tarpon was 0.97 km^2 (range 0.77–1.17 km^2), while the average KUD for all tarpon was 0.76 km^2 (range 0.08–0.99 km^2) (Table 2, Fig. 2). Overlap analysis of daytime activity space was very low during the year, with each tarpon showing distinct core areas (50% KUD overlap: mean = 12.3% ± 20.7 SD, range = 0–50%) and activity spaces (95% KUD overlap: 46.2% ± 29.0 SD, range = 18–95%). The 50% KUD areas were centered around northwest corner of runway (36032), around Black Point and deeper part of Brewers Bay (2966), in and around the lagoon and Range Cay extending to shallow and deep parts of Brewers Bay (10979) and around the tip of runway (10980) (Fig. 2). Nighttime 50% and 95% KUD space overlap increased to 26.2% ± 39.2 SD (range = 0–100%) and 60.0 ± 25.6 SD (range = 28–98%), respectively, primarily due to tarpon moving into lagoon at night (Fig. 2). In April, however, daytime 50% and 95% KUD space overlap increased to 25.3% ± 13.0 SD (range = 11–36%) and 65.2% ± 14.0 SD (range = 56–81%), respectively, when they shifted their activity space to similar areas within Brewers Bay, particularly towards Range Cay, shallow Brewers Bay beach and mid Brewers Bay (Fig. 3). Excluding the month of April, daytime 50% and 95% KUD space overlap declined to 7.7% ± 8.8 SD (range = 0–20%) and 32.8% ± 20.6 SD (range = 11–52%), respectively. Dawn and dusk crepuscular periods, which represented the transition between night and day activity spaces (Fig. 2) were nearly identical for both 50% and 95%

KUDs across diel and crepuscular periods (RM-ANOVA 50% KUD: $F_{1,11}$ = 3.925, P = 0.073; 95% KUD: $F_{1,11}$ = 0.650, P = 0.44) and across months (RM-ANOVA 50% KUD: $F_{1,32}$ = 0.077, P = 0.78; 95% KUD: $F_{1,32}$ = 1.119, P = 0.29).

Table 2

Calculated home range size (km^2) for each tarpon based on 50% and 95% KUD and 100% MCP; number of COA points that fell on land and total percentage of COA points on land removed out of total COA points used for home range analyses.

Fish ID	Total number of COA points	MCP 100% area (km2)	KUD 95% area (km^2)	KUD 50% area (km^2)	Number of COA points on land	Percentage of COA points removed
2966	19367	1.174504	0.988447	0.200319	123	0.64
10979	11888	1.055597	0.619165	0.07481	163	1.37
10980	10425	0.86472	0.492339	0.090001	166	1.59
36032	887	0.767456[a]	0.938117	0.14922	7	0.79

[a] In this case 100% MCP is smaller than 95% KUD based on how they are calculated (see Methods).

Figure 2. Activity space of each tarpon based on yearlong 100% MCP (left), day (yellow/orange), night (blue/green), crepuscular (dawn = red, dusk = blue purple) time intervals using 50% and 95% kernel utilization distribution. Arrow represents an example of a corridor between day and night activity space. See Fig. 1 for labels.

Figure 3. Average 50% KUD activity space for April and remaining months (yearlong) of all tarpon combined.

Rate of Movement

Average rate of movement (ROM) of tarpon was 0.06 m/s (± 0.08 SD) and showed significant difference between day (mean = 0.05 m/s ± 0.06 SD), night (mean = 0.04 m/s ± 0.07 SD), dawn (mean = 0.10 m/s ± 0.09 SD) and dusk (mean = 0.10 m/s ± 0.04 SD) periods (ANOVA: $F_{1,3}$ = 117, P < 0.0001). Mean rate of movement was similar among crepuscular periods but significantly higher than diel periods (Tukey HSD: P < 0.0001) (Fig. 4) and ROM was significantly higher during the day compared to night (Tukey HSD: P < 0.0001). Diel ROM also varied across seasons (2-Way ANOVA: $F_{1,15}$ = 253.2, P < 0.0001). Most notable, daytime ROM was significantly lower in winter compared to other seasons (Tukey HSD: P < 0.001). During all seasons, crepuscular ROM peaked between 04:00 to 05:00 and 18:00 (Fig. 4). Monthly ROM was not significantly different across months (mean = 0.07 m/s ± 0.013 SD), but there was a strong relationship between monthly ROM and 50% KUD (F = 34.07, P = 0.0001, R^2 = 0.77) with the highest rates for both metrics during the months of April, June and September (Fig. 5).

Figure 4. Diel rate of movement of tarpon by season of the year: Spring (March, April, May), Summer (June, July, August), Fall (September, October, November) and Winter (December, January, February).

Figure 5. Relationship between average rate of movement (ROM) and core activity space (50% KUD) for four tarpon.

Vertical movement

Vertical movement of tarpon varied among time of the day (ANOVA: $F_{1,3}$= 36526, P < 0.0001) (Fig. 6). Tarpon used more of the water column during the day with average depths between 2–13 m and maximum depth range between 16–37 m. At night, tarpon stayed in shallower waters with depths ranging from 0–5 m, while maximum depth ranged between 8–14 m. Nighttime vertical movements were partly constrained when tarpon were in lagoon (maximum depth 4 m, Fig. 2). During dawn and dusk, average depth of tarpon ranged between 0–8 m (Fig. 6). Vertical distribution of tarpon varied across months (ANOVA: $F_{1,11}$ = 2599, P< 0.001), with tarpon remaining shallower in June and July (mean = 2.85 range ± 3.75 SD, range = 1-3.5 m) and deeper in November (mean = 6.83 range ± 6.25 SD, range 1–13 m).

Figure 6. Vertical movements of three Atlantic tarpon colored by diel and crepuscular periods with 0 of y axis representing the water surface. The box plot represents the average depth, the upper section of the box represents the first quartile, the middle line is the median, and the lower section is the third quartile. The upper line of box represents minimum depth and the lower line of box represents maximum depth. The dots outside the box and lines, represent the outlying depth points.

Movement and environmental variability

Water temperature in Brewers Bay varied from 25-28°C in winter to 29-32°C in late summer, was more variable inside the lagoon (mean = 28.3°C ± 1.27SD, range = 24.8–32.0°C) than in bay (mean = 28.1°C ± 1.15SD, range = 25.6–30.6°C) and had a strong effect on tarpon movement and habitat use. We found a significant negative relationship between number of tarpon detections and temperature in the lagoon at night (adjusted R^2 = 0.3179, P< 0.001), but no relationship between frequency of detections in the lagoon or around the runway at other times of day (Fig. 7). Tarpon were present in the lagoon at night when temperature ranged between 26-28°C; however, once temperature reached 29°C frequency of tarpon detections decreased rapidly and stopped at about 30.5°C (Fig. 7), indicating tarpon left the lagoon. Water temperatures in the lagoon reached or exceeded 30.5°C nearly 60 d of the study period (Table 3). At times of high lagoon temperatures, tarpon had higher frequency of detections along the tip and south side of the airport runway (i.e. stations 248, 249, 285, 251, 282; Fig. 1) where night-time water temperature reached only 29°C (Fig. 7).

Figure 7. Diel relationship between average number of tarpon detections and water temperature (°C) within the lagoon and along the airport runway.

Table 3
Count of days at given temperature range for the lagoon and runway.

Temperature (°C)															
	25	25.5	26	26.5	27	27.5	28	28.5	29	29.5	30	30.5	31	31.5	32
Lagoon	1	10	50	122	219	178	118	165	245	256	156	33	5	17	4
Runway	0	0	16	69	185	100	74	143	161	166	83	4	0	0	0

Similar to water temperature, dissolved oxygen concentrations in lagoon varied widely from 0–14 mg/L (mean = 4.85 ± 1.89SD) but were more stable along the airport runway (mean = 6.32 ± 1.89SD, range 6.3–9.5 mg/L). Based on detection frequencies, there was no significant relationship in number of detections of tarpon at different levels of dissolved oxygen within the lagoon or the runway, indicating that tarpon seemed to tolerate the low oxygen levels in the lagoon, especially at night.

In September 2017, two category 5 hurricanes, Irma and Maria, impacted the USVI. During Hurricane Irma tarpon 2966 moved to deeper water then was absent from the bay for 5 hours (September 6 from 11:26 – 16:17) when the hurricane passed directly over St. Thomas (wind speeds of 100–150 km/h, pressure of 979 hPa). During Hurricane Maria, which passed about 150 km southwest of St. Thomas, tarpon 2966 maintained much of its normal behavior.

Discussion

This was the first study to use passive acoustic telemetry to illustrate small-scale three-dimensional movement patterns of Atlantic tarpon (61–95 cm-FL) in a small bay (1.8 km^2) in the US Caribbean. Most tarpon were transient (67%), leaving the bay shortly after tagging, with one (ID 10979) returning to its home range two months later and another (ID 36032) being detected at an acoustic array 12 km offshore (i.e. [28]).This transitory nature is not unusual for highly migratory species [6, 16, 17, 48, 49]. Both tarpon were 95 cm FL (two of the largest tarpon in this study) and could have been sexually mature males and potentially participated in reproduction [17, 22, 24]. Despite high rates of movement, the remaining resident fish (33%) each had distinct daytime home ranges, small areas (0.07 to 0.20 km^2) of Brewers Bay with very low overlap (< 8%). At night, however, all resident tarpon moved into or near a small, shallow lagoon. During crepuscular periods, tarpon had the highest rates of movement and higher overlap in space use, indicating consistent use of migration pathways at dawn and dusk, which is similar to many other species [20, 50–56]. The spatial patterns displayed by tarpon suggest habitat partitioning during daytime and sheltering and protection from predation in the lagoon at night [6, 17, 19, 20]. However, since tarpon tend to feed at sunset and continue feeding into the night if there is enough food and available light for foraging [21, 57], lower night time ROM may indicate that tarpon were either sheltering in the lagoon or their food supply was concentrated and easier to catch at night.

Distinct seasonal patterns in behavior of tarpon were observed. Seasonal movements of Atlantic tarpon have been attributed to food availability, reproductive maturity (spawning aggregations) and changes in environmental conditions (i.e., temperature, dissolve oxygen) [6, 17, 21, 49, 58]. Tarpon showed a strong positive relationship between ROM and 50% KUD among months as well as variability in ROM across seasons, a finding not reported before. Tarpon had slower ROM in winter months and higher ROM during spring months. During the month of April tarpon increased their ROM and overlap in daytime activity space tripled from 8–25%. These changes in behavior and activity space coincided with the arrival of schools of bait fish as well as nesting seabirds that also feed on bait fish in the spring [59, 60]. Tarpon can increase their foraging success in the presence of seabirds feeding on bait fish at the water surface [59, 61]. When seabirds were present, we observed groups of tarpon foraging near the surface on bait fish during the spring months along the airport runway, Range Cay, the middle of Brewers Bay and Black Point reef (Duffing Romero, M. and Nemeth, R.S., *pers. observations*). The areas of Brewers Bay where this feeding behavior was observed corresponded to April daytime activity space of tagged tarpon (Fig. 3)

Resident fish generally stayed less than 10 m depth, which is typical for tarpon [6, 17], but occasionally went to 25 m. Many coastal pelagic fish, such as barracuda (*S. barracuda*), white marlin (*K. albida*), dolphinfish (*C. hippurus*) and many species of tuna show similar vertical movement patterns, where they spend the majority of time at shallow depths or close to the surface and then make diel/seasonal deep water movements [62–64].

Extreme environmental conditions influenced tarpon behavior in Brewers Bay. Tarpon prefer water temperatures from 24–26°C in spring and fall and 28–30°C in summer [6, 17, 26]. Our results indicated that tarpon avoided water temperatures greater than 30°C. For instance, tarpon detection frequencies within the lagoon decreased at temperatures above 29°C and they did not enter nor rest in the lagoon at night when water temperature was higher than 30.5°C, but instead moved to deeper water on the south side of airport runway. At this threshold temperature, tarpon faced a trade-off of remaining in higher temperatures within the protected lagoon or leaving the lagoon for cooler, less protected waters around the airport runway at night. Previous studies on barracuda (*Sphyraena barracuda*) and bonefish (*Albula vulpes*) have shown that both species move to deeper waters away from their home range to avoid seasonal weather patterns and associated temperature fluctuations [21, 48]. Despite the effect of high water temperatures, tarpon tolerated low dissolved oxygen concentration in the lagoon, which is attributed to being facultative air-breathers [17, 65]. The movement and behavior of one tarpon also changed significantly in response to category 5 hurricanes Irma and Maria. We found that tarpon 2966 expanded its space use throughout Brewers Bay and the waters of the airport runway; as well as moved to deeper waters and away from the array as the eye of hurricane Irma was passing. These types of responses are typical of marine animals exposed to hurricane conditions, but the degree of response may differ among species depending upon their vulnerability to habitat damage from storm surge [35, 66]. Overall, these results are particularly important with regards to climate change and its impacts to water quality and storm severity and frequency, and the distribution of fish species [35, 67, 68].

Conclusion

Direct measurement of home range, habitat utilization and changes in movement behavior of Atlantic tarpon provided key insights into monitoring and managing this species in the US Virgin Islands. For instance, understanding the percent of transient and resident tarpon populations and having an estimate of home range and movement behavior of resident Atlantic tarpon allows resource managers to implement more effective management of this important sport fishery. Similarly, understanding seasonal trends in movement patterns of tarpon allow resource managers to make predictions on tarpon movement to different locations with changes in resource availability (i.e., food, mates, habitat) and water quality (i.e., temperature, dissolve oxygen) [1, 2, 56, 69].

Abbreviations

COA
Center of Activity; MCP:Minimum Convex Polygon; KUD:Kernel Utilization Distribution; ROM:rate of movement; HR:home range

Declarations

Ethics and consent to participate

All capture and tagging methodology on all fish in Brewers Bay was approved by the University of the Virgin Islands Institutional Animal Care and Use Committee (IRB #747807-1).

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interest

The authors declare that they have no competing interests.

Authors contributions

MDDR conducted most of the field work, data analyses/interpretation and writing; JKM contributed to data management/analyses; RSN secured funding for project and contributed to field work; JL, SJP, JKM, JSA and RSN contributed to data interpretation and writing of manuscript.

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Figures

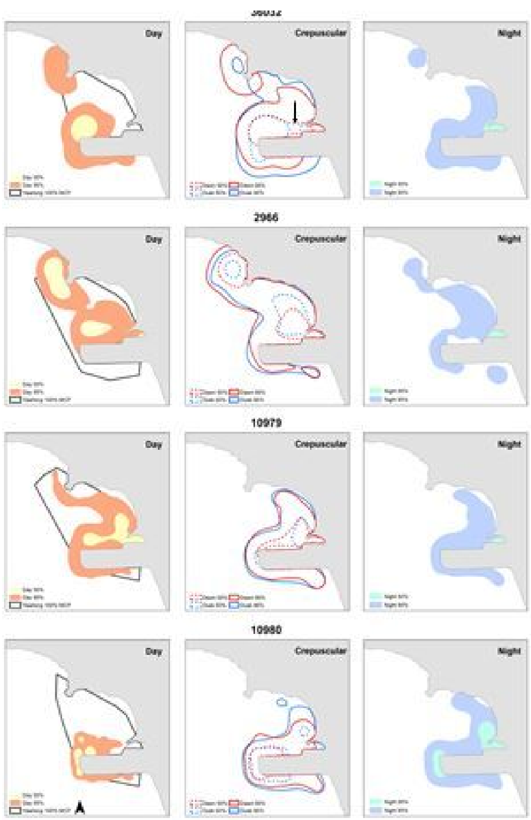

Figure 1

Map of the Caribbean (A) and the island of St. Thomas in the U.S Virgin Islands (B) and study site in Brewers Bay (C) depicting bathymetry and the acoustic array with its station number and approximate range of 70% detection probability (circles). The detections ranges vary by habitat (deep hard bottom=115m, deep soft bottom=120m, shallow soft and hard bottom= 101m) based on range testing [34]. Location of environmental data logger stations shown as green dots (temperature) and red diamonds (dissolved oxygen). Yellow dots represent approximate location where Atlantic tarpon were caught and released.

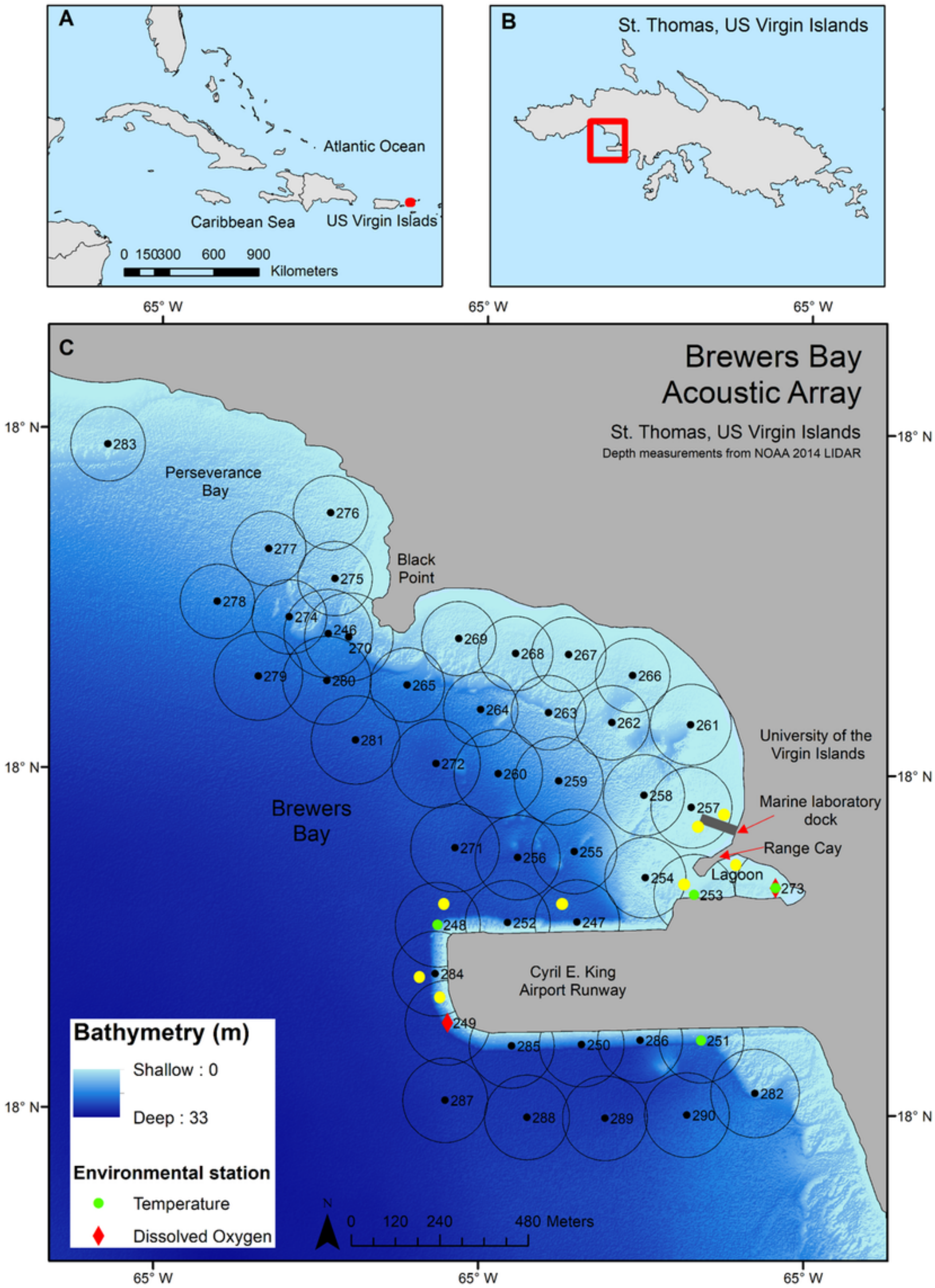

Figure 2

Activity space of each tarpon based on yearlong 100 % MCP (left), day (yellow/orange), night (blue/green), crepuscular (dawn = red, dusk = blue purple) time intervals using 50% and 95% kernel utilization distribution. Arrow represents an example of a corridor between day and night activity space. See Fig. 1 for labels.

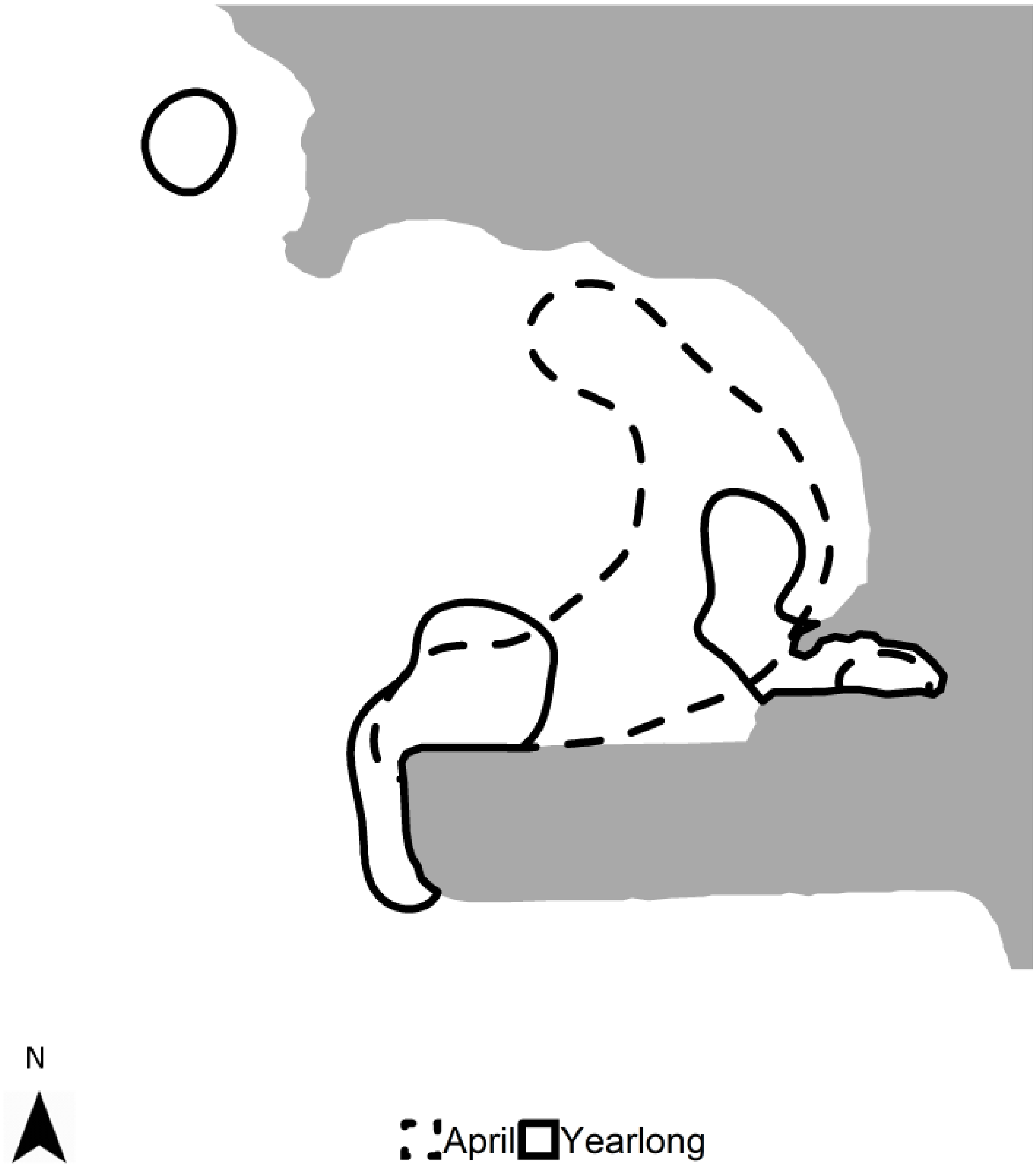

Figure 3

Average 50% KUD activity space for April and remaining months (yearlong) of all tarpon combined.

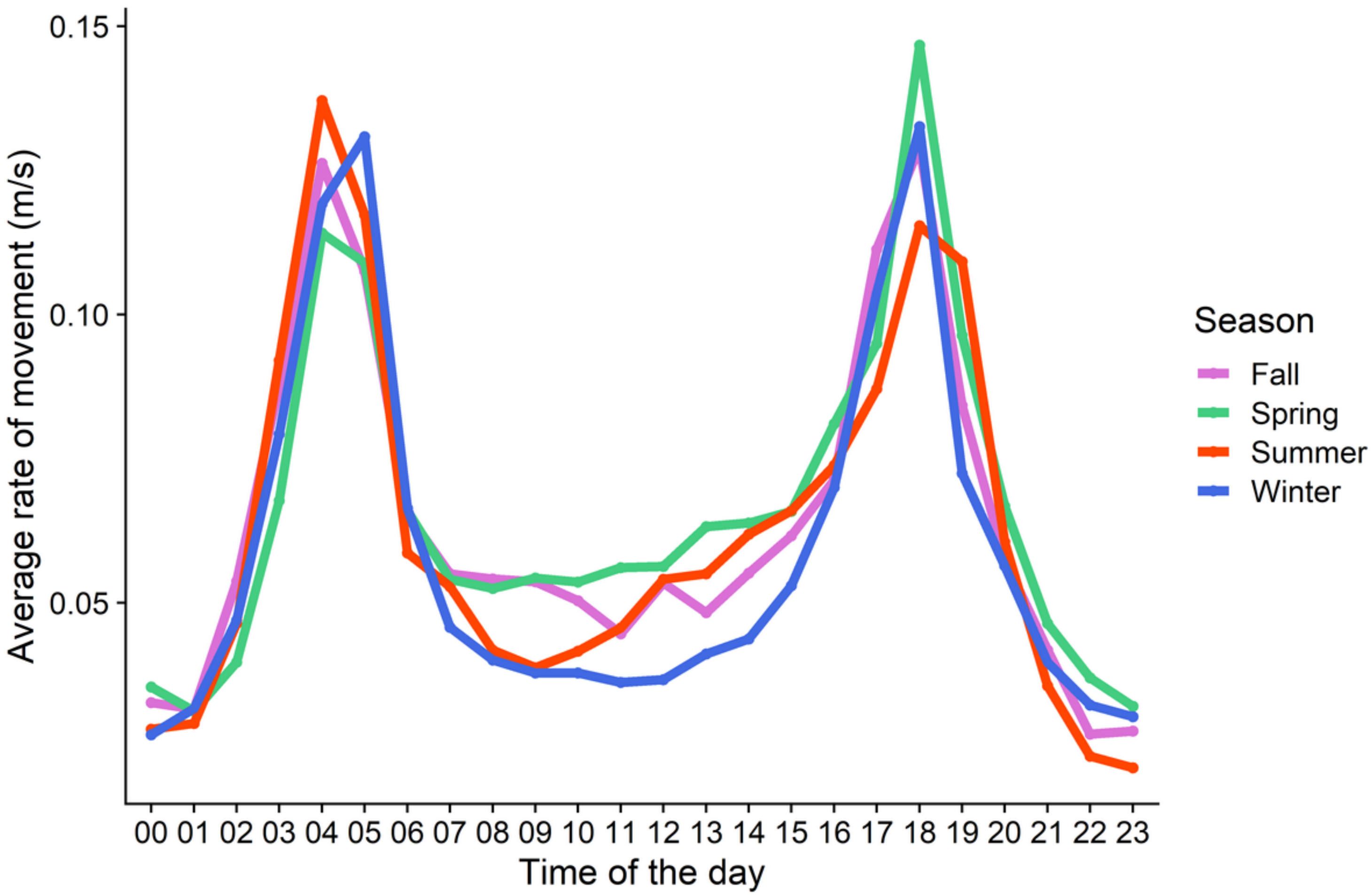

Figure 4

Diel rate of movement of tarpon by season of the year: Spring (March, April, May), Summer (June, July, August), Fall (September, October, November) and Winter (December, January, February).

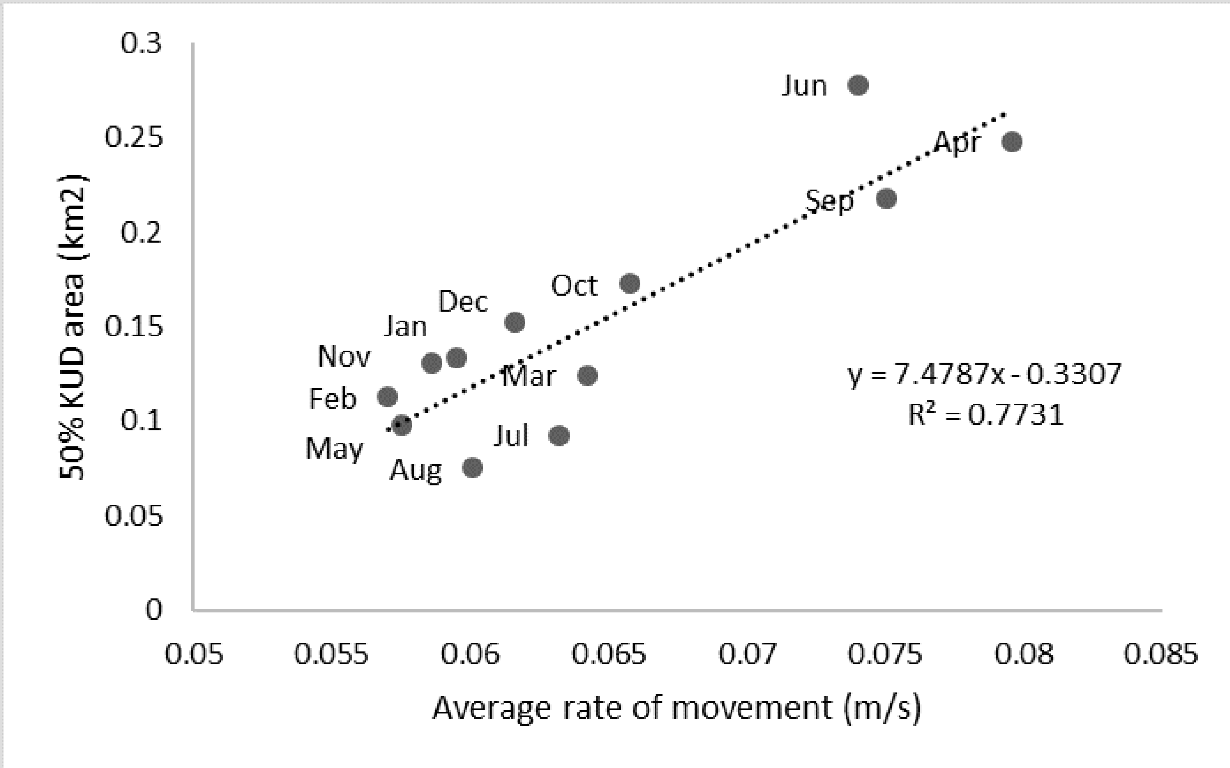

Figure 5

Relationship between average rate of movement (ROM) and core activity space (50% KUD) for four tarpon.

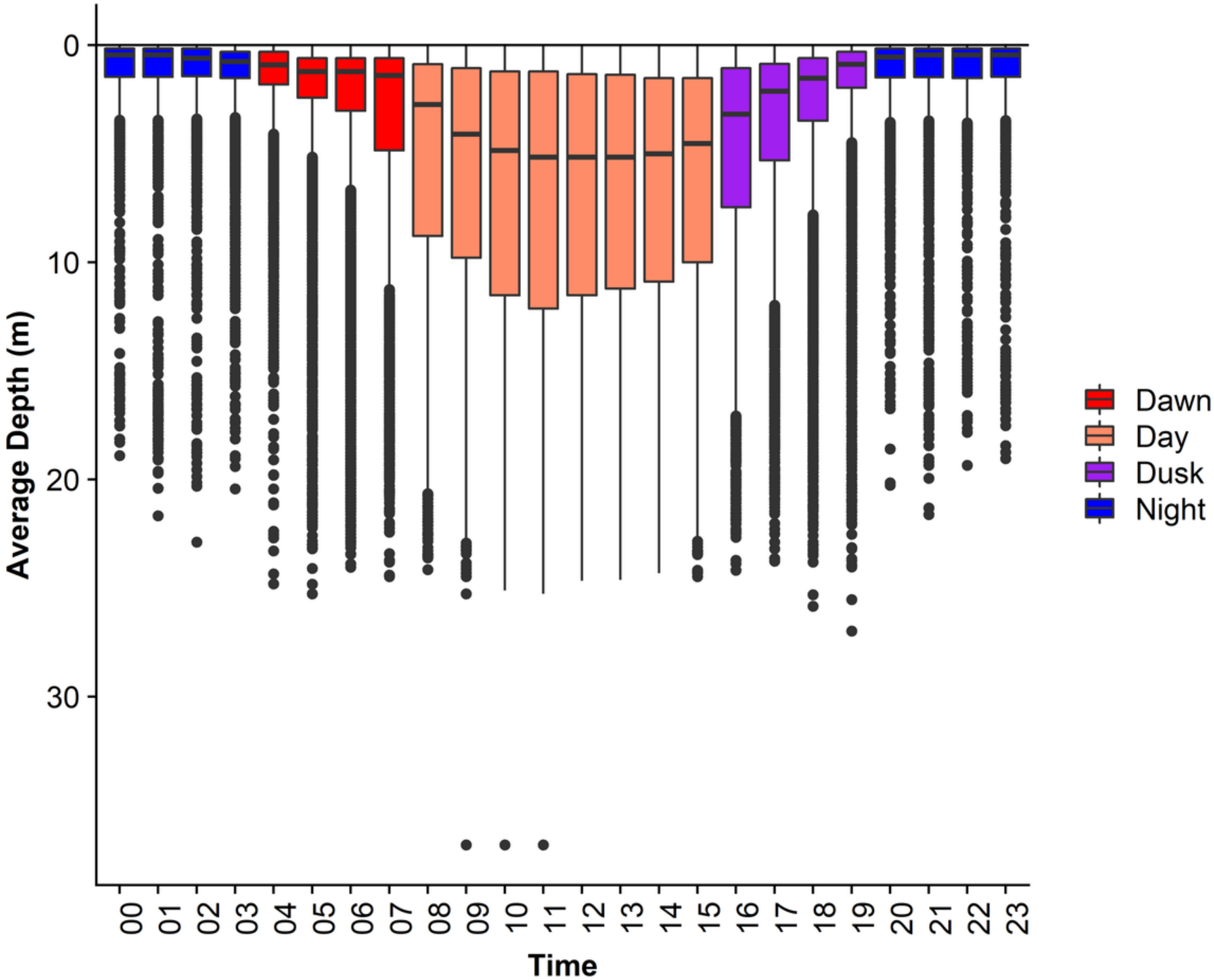

Figure 6

Vertical movements of three Atlantic tarpon colored by diel and crepuscular periods with 0 of y axis representing the water surface. The box plot represents the average depth, the upper section of the box represents the first quartile, the middle line is the median, and the lower section is the third quartile. The upper line of box represents minimum depth and the lower line of box represents maximum depth. The dots outside the box and lines, represent the outlying depth points.

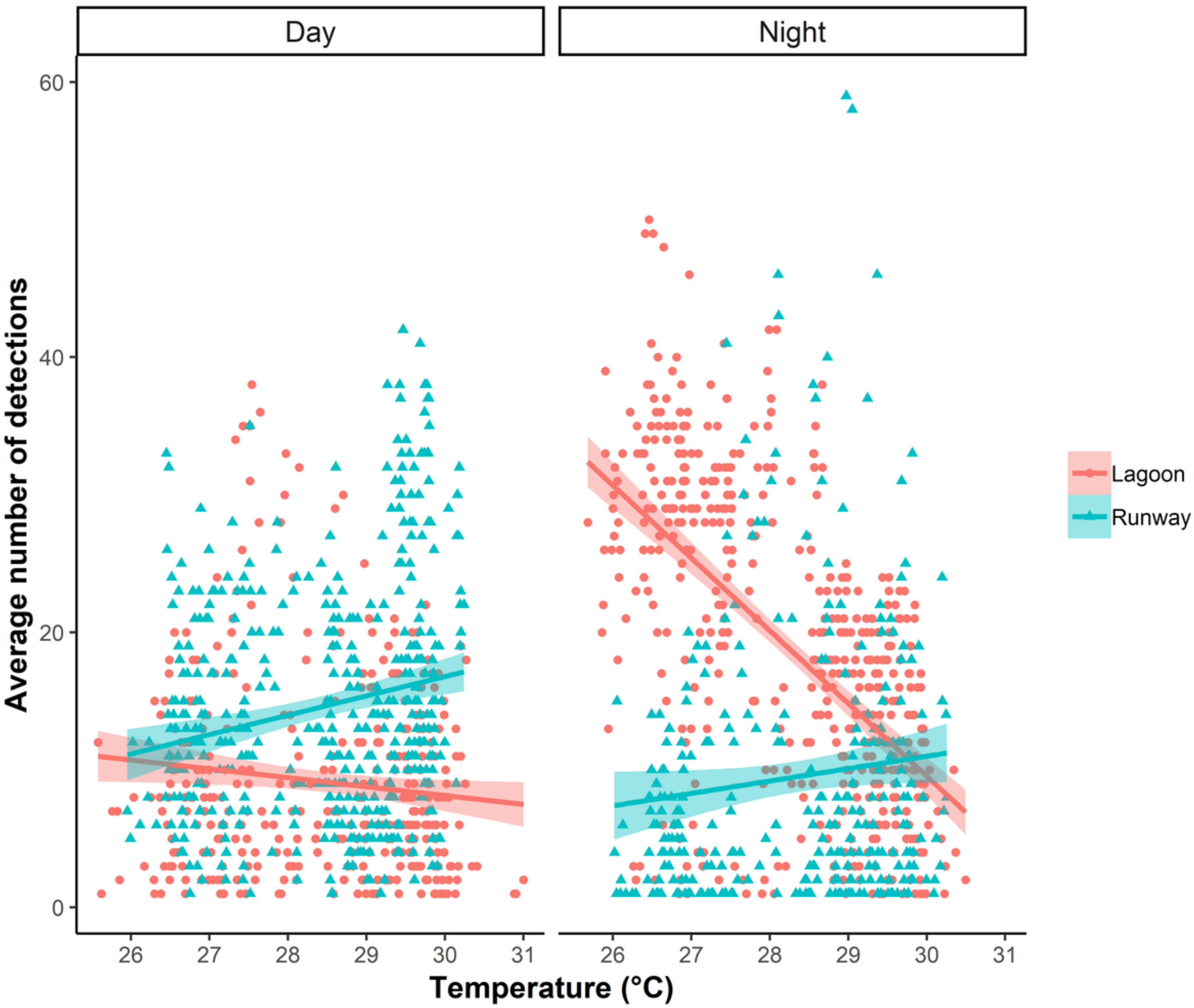

Figure 7

Diel relationship between average number of tarpon detections and water temperature (C) within the lagoon and along the airport runway.