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Regional movements of the tiger shark, *Galeocerdo cuvier*, off northeastern Brazil: inferences regarding shark attack hazard

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ABSTRACT

An abnormally high shark attack rate verified off Recife could be related to migratory behavior of tiger sharks. This situation started after the construction of the Suape port to the south of Recife. A previous study suggested that attacking sharks could be following northward currents and that they were being attracted shoreward by approaching vessels. In this scenario, such northward movement pattern could imply a higher probability of sharks accessing the littoral area of Recife after leaving Suape. Pop-up satellite archival tags were deployed on five tiger sharks caught off Recife to assess their movement patterns off northeastern Brazil. All tags transmitted from northward latitudes after 7-74 days of freedom. The shorter, soak distance between deployment and pop-up locations ranged between 33-209 km and implied minimum average speeds of 0.02-0.98 km.h^{-1}. Both pop-up locations and depth data suggest that tiger shark movements were conducted mostly over the continental shelf. The smaller sharks moved to deeper waters within 24 hours after releasing, but they assumed a shallower (< 50 m) vertical distribution for most of the monitoring period. While presenting the first data on tiger shark movements in the South Atlantic, this study also adds new information for the reasoning of the high shark attack rate verified in this region.

Key words: migration, Recife, satellite telemetry, shark attack, Suape.

INTRODUCTION

Understanding the factors that elicit repeated shark attack events on humans in a local scale is essential in every sort of aspects. Since 1992, the metropolitan region of Recife, Brazil, exhibits one the highest shark attack rates per unit of area in the world, accounting for 53 attacks which resulted in 20 fatalities. Relative abundances assessed off Recife (Fischer et al. 2009), together with forensic analysis (Gadig and Sazima 2003, Hazin et al. 2008) indicated the tiger shark, *Galeocerdo cuvier*, and the bull shark, *Carcharhinus leucas*, to be responsible for most of the attacks. Both species are considered potentially aggressive and have been frequently implicated in attacks on humans worldwide (International Shark Attack File, http://www.flmnh.ufl.edu/fish/Sharks/ISAF/ISAF.htm. Accessed January 26, 2011).

Hazin et al. (2008) suggested that the construction of a port complex in Suape, about 20

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km to the south of Recife, was the main factor responsible for the attack outbreak due not only to strong environmental degradation, resulting from construction activities, but also to increased attraction of sharks into this area in association with higher maritime traffic. Sharks are known to follow ships (Baldridge 1974, Schultz 1975) and to visit port areas and harbors (Coppleson 1958, McCord and Lamberth 2009, Meyer et al. 2009). Attraction of sharks by low-frequency sounds (Myrberg 2001) emitted by transiting vessels (Averson and Vendittis 2000) could partially explain such behavior, as well as the common habit of ship crews to throw garbage overboard. Thus, it is likely that the Suape port may have favored the approximation of sharks to these shores. Hazin et al. (2008) suggested that potentially aggressive sharks occurring off Recife could be moving downstream following northward coastal currents, which would lead them from the coast of Suape directly to the beaches of Recife where most attacks occurred. This would be most applicable in relation to tiger sharks, which have wide home ranges (Meyer et al. 2009) and have been reported to perform long-distance movements in a short amount of time (Heithaus et al. 2007, Kohler et al. 1998). If tiger sharks off northeastern Brazil are moving northward then, under the assumption that sharks are being attracted shoreward towards Suape by incoming vessels, one might predict that they would subsequently visit the littoral area of Recife. This note investigates the regional movements of tiger sharks caught off Recife and addresses the implications of such movements regarding local attack hazard.

MATERIALS AND METHODS

Recife is located in the northeastern Brazilian coast (8°03’S, 34°53’W; Fig. 1), about 20 km to the north of the Suape port. The Suape port was built in a large, mangrove-bordered estuarine system which used to be relatively pristine until construction activities inflicted intense habitat degradation, including the partial barring of two of the four rivers previously discharging in this system. In the metropolitan region of Recife, the area where most of the attacks occurred corresponds to a 20 km stretch of densely populated beaches, which includes the Barra de Jangadas estuary. The continental margin of northeastern Brazil consists of a narrow, 63 km width shelf (Souza 2007) bordered by one of the longest, consistently steep (4 to 20°) slopes in the world (Fainstein and Milliman 1979). In this region, coastal currents assume a northward direction almost all year-round (Stramma 1991, Stramma et al. 1995, Bittencourt et al. 2005).

Pop-up satellite archival (PSAT) tags (model mk10; Wildlife Computers, Washington) were deployed on 5 tiger sharks (T1-T5; Table I) caught off Recife between 2008 and 2010 during the winter season (June-August), since winter presented higher shark attack rates (Hazin et al. 2008). All sharks were caught within 2.0 km from shore between 8-12 m isobaths, using a bottom longline equipped with 10 m length branch lines and 18/0, 0% offset circle hooks, except for T3 which was caught 17 km from shore at about 30 m depth. All sharks were carefully brought onboard, eye-covered, and restrained on deck (T1 and T2) or in a wooden tank filled with sea water (T3, T4 and T5), which was readily assembled after the shark was first sighted. Sharks were then quickly transported offshore in order to remove them away from the area of risk, and released at isobaths between 20-40 m, depending on oceanographic conditions and the health status of the shark. Before releasing, sharks were measured, sexed, and tagged with both a conventional, stainless steel, dart tag, and a PSAT-tag. The conventional tag was fitted to the dorsal musculature just below the first dorsal fin, while the PSAT-tag was attached to the proximal, anterior region of the first dorsal fin by passing a coated, 2.0 mm polyamide monofilament through a hole pierced with a 3.0 mm gauge needle and tightly adjusting the length of the monofilament to prevent the tag from crossing over the dorsal fin towards

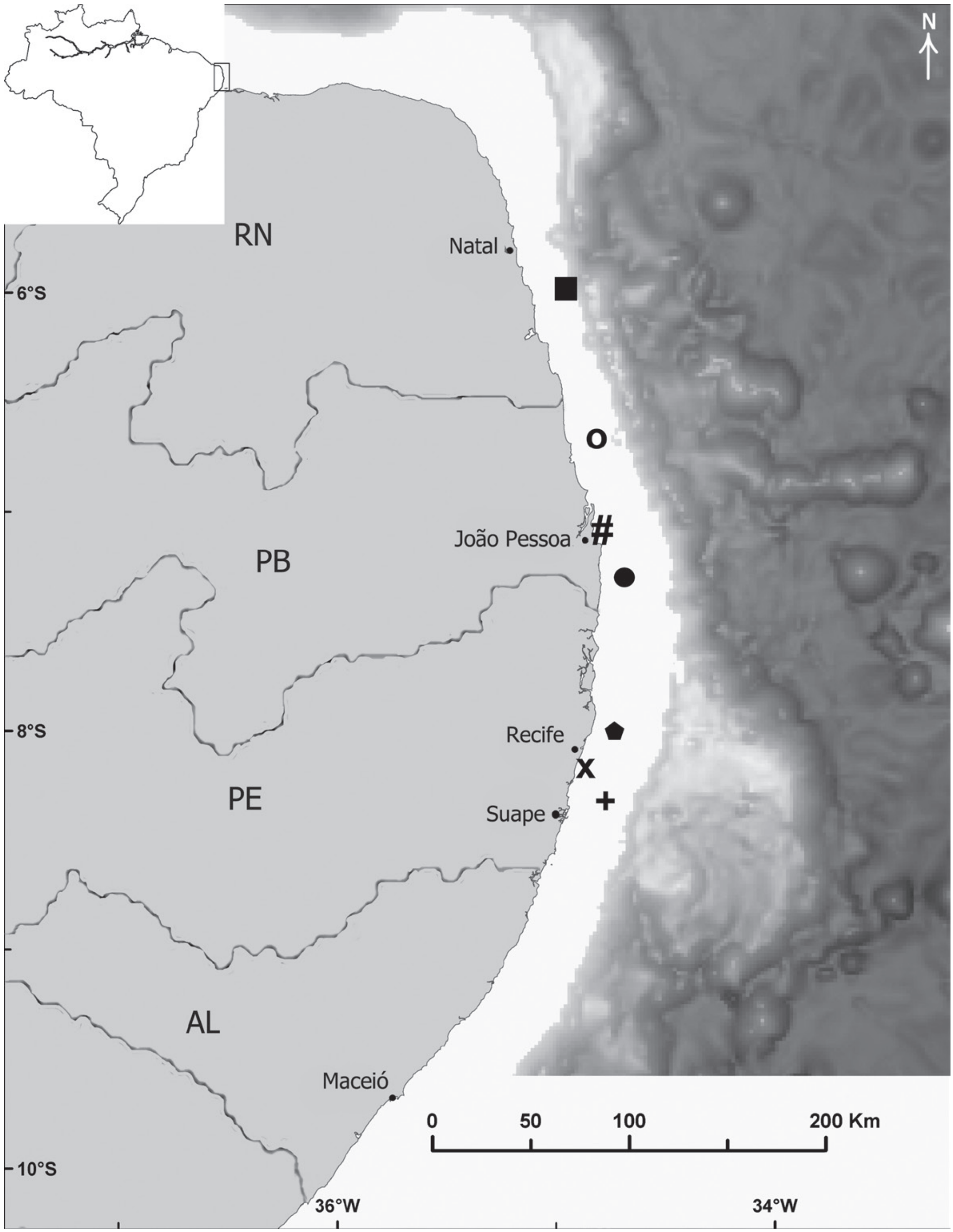

Figure 1 - Deployment and pop-up location of Pop-up Satellite Archival Tags (PSAT) fitted on five tiger sharks caught off Recife, Brazil. On the map, locations are represented by: Cross = T1, T2, T4, and T5 tag deployments; plus sign = T3 tag deployment; solid square = T1 tag pop-up; empty circle = T2 tag first transmission; solid circle = T2 tag pop-up location estimate; solid pentagon = T3 tag pop-up; hash mark = T5 tag first transmission. The darkness gradient in the oceanic region is directly proportional to water depth relatively to the continental shelf, which is represented in white.

its anterior region while being towed by the shark. Every procedure carried out with sharks was conducted in accordance to the recommendations at the Regiment of the Commission of Ethics on the Usage of Animals from the Universidade Federal Rural de Pernambuco. This study was ethically approved by the license number 041/2009 (protocol number 23082.009679/2009 D18). All tiger sharks were juveniles, measuring 128-193 cm TL, and were released in good health, generally swimming away from the boat immediately after being returned to the water except for T4, which had to be assisted during approximately 15 min before demonstrating enough strength for being released.

PSAT-tags were programmed to release between 30-99 days after deployment (Table I). Water depth and temperature were recorded every second and further summarized into bins of between 2-24 hours for transmitting during satellite uplinks, which occurs once the tag pops off the shark and floats to the surface. Depth and temperature data were binned in 14 strata that were set before deployment. The time spent at each stratum was continuously monitored. Disregarding minor variations, depth strata were generally arranged by classes < 0, 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-125, 125-150, 150-200, 200-250, 250-300, and > 300 m. Temperature strata were arranged by classes < 12, 12-14, 14-16, 16-18, 18-20, 20-22, 22-24, 24-25, 25-26, 26-27, 27-28, 28-29, 29-30, and > 30 °C. Heterogeneous strata sizes required temporal data to be standardized by either depth- or temperature-unit before assessing tiger shark environmental preferences. Data analysis was performed with *R* 2.12.2 (*R* development core team 2011) and IGOR Pro 6.1®. In one circumstance, the pop-up position was derived from surface current direction and speed which were estimated based on tag drift during the first 24 hours of satellite-linked transmissions using only messages with location quality LC ≥ 1 (Argos-based geolocation error < 1 km for LQ ≥ 1) (Hays et al. 2001). Luminosity-based geolocation estimates, which provide a proxy of the horizontal movements performed by the tagged individual during the tracking period, were not considered because position estimates errors at tropical latitudes are yet too great for assessing movements conducted in small spatial scales and thus are most effective for studies conducted in the oceanic realm (Musyl et al. 2011).

TABLE I
Summary of PAT-tag deployments on tiger sharks off Recife, Brazil between 2008-2010. Tagging location was about [8.1 S; 34.8 W] for all sharks except for T3 [8.25 S; 34.77 W]. Note that T4 tag uplinked to the satellite insufficient times and so pop-up location and tracking data are not available (n.a.).

Tag	Sex	TL (cm)	Tag date	Prog. span	Track span	Pop-up location	Linear distance (km)	Km from shore	Max. depth (m)	Min. Avg. speed ($km.h^{-1}$)	ΔTemp. (ºC)	Hours. Bin-1
T1	M	130	28-Jun-08	30 d	30 d	6.32S;34.79W	209	23	248	0.29	13.6 – 27.0	24
T2	M	193	25-Jul-09	75 d	4 d	7.34S;34.65W*	94*	16	56	0.98	25.0 – 27.6	3
T3	F	128	1-Jun-10	73 d	74 d	7.97S;34.67W	33	15	200	0.01	15.0 – 29.0	3
T4	F	154	1-Aug-10	50 d	42 d	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2
T5	M	150	7-Aug-10	99 d	72 d	7.08S;34.85W**	125**	inland**	304	n.a.	13.0 – 28.0	4

*estimated from tag drift;
**relative to first transmission.

RESULTS

Following pop-up, all satellite tags transmitted to the north of Recife at linear distances varying between 33 and 209 km from the deployment location (Fig. 1), except for T4 tag. Although the T4 tag transmitted a few messages by the programmed pop-up date, the amount of consecutive transmissions were insufficient for generating a geolocation estimate, what could be ascribed to a technical failure such as the antennae being damaged during the deployment. Due to some premature releases, tracking duration varied between 4 and 74 days (Table I). T2 tag transmitted 7 days after deployment, about 152 km to the north of Recife (Fig. 1); however, data analysis showed that the tag had been drifting at the surface for about 3 days before transmitting to the satellite (Fig. 2B). Estimated pop-up position derived from surface current direction (about 10° NW) and speed (0.25 $m.s^{-1}$) corresponded to 94 km northward from the tagging location (7.34° S; 34.65° W). The first transmission of 3 out of the 4 successfully deployed tags occurred at 15-23 km from the coastline. T5 tag also prematurely released but it was washed up to the beach before transmitting (3 days after releasing) and so the estimate of pop-up position was impossible to assess. Assuming the shorter, soak course between deployment and pop-up locations, calculated minimum average speeds were low for both T1 and T3 (0.29 and 0.02 $km.h^{-1}$, respectively), but higher for T2 (mean speed of 0.98 $km.h^{-1}$, equaling to 0.13 body length per second).

The vertical depth-and-temperature profiles were relatively consistent among all tracks. T1, T3 and T5 showed a clear tendency for occupying deeper water layers during the first ~13 days of tracking, frequently performing dives between 150-300 m deep (Fig. 2). T5 performed the deepest

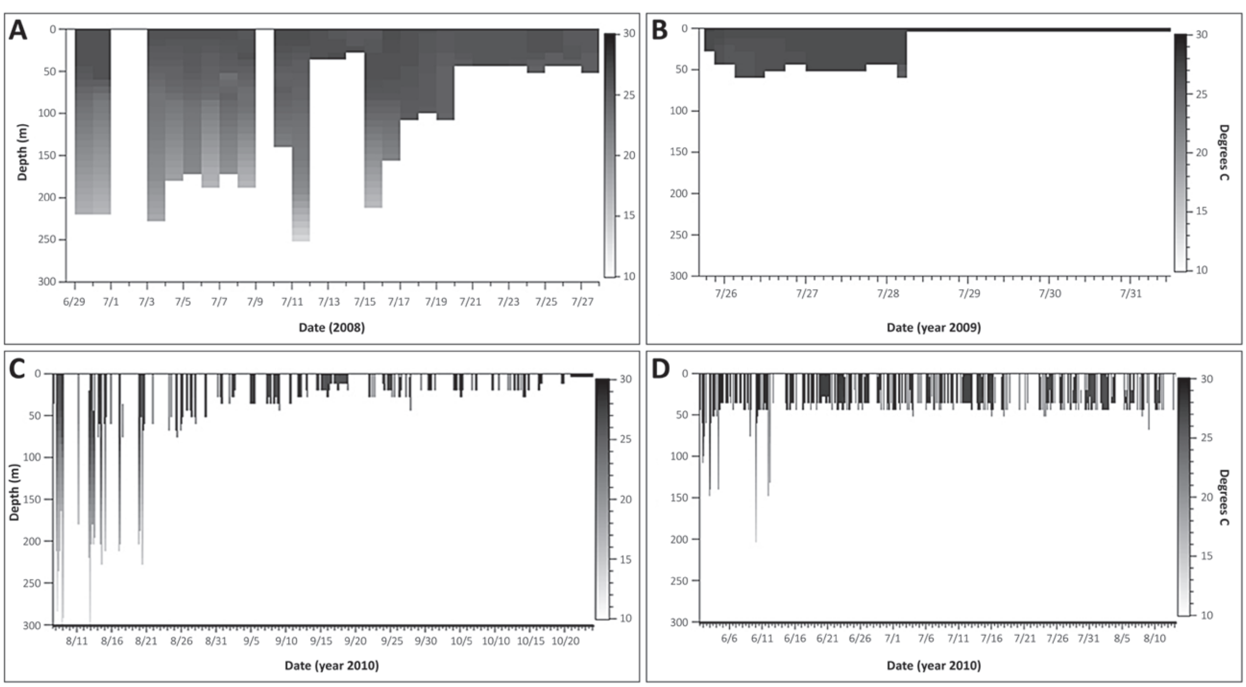

Figure 2 - Depth-and-temperature profiles of the vertical movements performed by tiger shark (A) T1, (B) T2, (C) T3, and (D) T5 off Northeastern Brazil. Data illustrates the depth range and associated water temperature per each time-unit successfully sampled and blanks correspond to data which was not successfully up-linked to ARGOS satellites. Note that both tags T2 and T5 prematurely detached off the animals and drifted on the surface for 3 days before transmitting. Data pertains to years 2008 (T1), 2009 (T2), and 2010 (T3 and T5).

dive observed (= 304 m). The thermal gradients of the dives of these three sharks went up to 13.4 °C, indicating deep penetration into the thermocline layer. After that first period, the sharks assumed a more superficial behavior for the remainder of the tracking period, generally never exceeding the 50 m isobaths, except for T1 which repeated the deep-diving pattern soon after for a couple of days (Fig. 2A). Despite being tracked for only 4 days, T2 movements were conducted exclusively in shallow water (< 56 m) in an environment with very little thermal variation (Fig. 2B), resulting in a quite homogeneous depth-and-temperature profile which was similar to the profiles of the other three sharks when their movements were restricted to more superficial waters. All the individuals moved to the surface during just about every temporal unit of the respective track.

Overall, all the individuals showed a strong preference for shallower waters, spending on average 52.5% (SD = 6.5%) of the tracking time at depths < 10 m and 88.0% (SD = 7.5%) at depths < 40 m (Fig. 3A). T5 spent the least amount of time (44.5%) at depths < 10 m, while T2 spent most of the time (59.7%) at those same depths. T3 spent the least amount of time (1.6%) at depths > 40 m. Standardization of depth strata further reduced the time per unit of depth spent by all sharks at deeper waters and it increased the time per unit of depth spent at isobaths < 10 m (average = 81.6%, SD = 7.8%). Generally, all sharks exhibited a decreasing preference for water layers deeper than 10 m, except for T3, which spent twice as much time per unit of depth at depths between 20-40 m than between 10-20 m (Fig. 3B).

All sharks spent most of the tracking time (average = 94.6%, SD = 6.8%) between 24-28°C. T1, T2 and T3 spent considerable time (average = 84.3%, SD = 9.9%) at warmer waters, between 26-28°C, while T5 spent 74.8% of the tracking time between 24-26°C and only 20.0% between 26-28°C (Fig. 4).

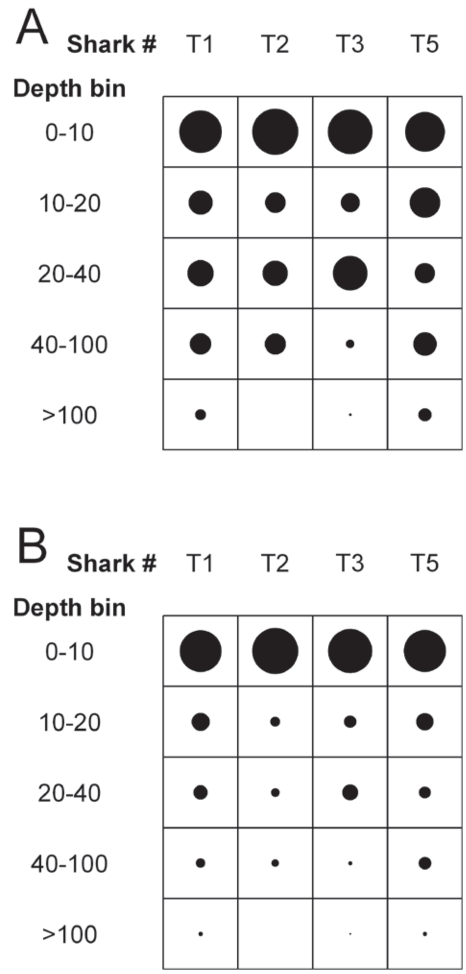

Figure 3 - Proportion of time spent by tiger sharks T1, T2, T3 and T4 at each depth strata for the entire tracking period considering (**A**) the raw time data as provided by the tag manufacturer, and (**B**) the depth-standardized time data for each depth bin as the relative time per unit of depth. The diameter of each circle is directly proportional to the cubic root of relative time in order to reduce differences between circle sizes of different depth strata. Plot produced in R version 2.12.2 with balloonplot function from Wickham (2009).

DISCUSSION

The present results sustain the hypothesis that tiger sharks occurring off Recife perform regional northward movements, following the direction of coastal currents. Long-distance movements of tiger sharks in both coastal and oceanic realms have been evidenced in previous studies (Heithaus et al. 2007, Kohler et al. 1998), and seasonal migrations

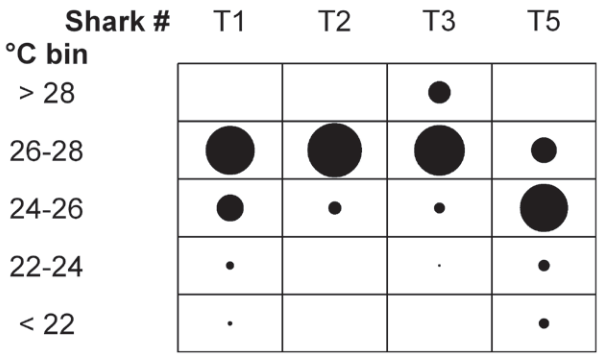

Figure 4 - Proportion of time spent by tiger sharks T1, T2, T3 and T4 at each temperature strata for the entire tracking period. The diameter of each circle is directly proportional to the cubic root of relative time in order to reduce differences between circle sizes of different temperature strata. Plot produced in R version 2.12.2 with balloonplot function from Wickham (2009).

were suggested to occur in some regions (Heithaus 2001, Wirsing et al. 2006). In Hawaii, tiger sharks were noted to move throughout wide-ranging, coastal habitats (15-109 km) which they patrol during a period of time before leaving to a different area (Meyer et al. 2009). Unfortunately, the poor quality of luminosity-based geolocation in tropical waters, most especially regarding latitude estimates (Musyl et al. 2001), did not allow the assessment of directional shifts of latitudinal displacement which could indicate patrolling behavior. Nevertheless, the close proximity of T3 tag to the original deployment location after a long period of time (74 days) suggests that such behavior may have occurred. It contrasted with T2 horizontal movement which produced a considerable displacement in little time, thus indicating a relatively well oriented course northwardly after being tagged off Recife. In any case, if patrolling behavior occurs in tiger sharks off northeastern Brazil, the overall net displacement appears to be directional, aiming to the north, since no tag transmitted to the south of Recife.

Tagged individuals were all juveniles measuring < 200 cm TL because the majority of the tiger sharks caught off Recife belong to that size-class, exceeding the number of larger specimens by 10-fold. They were by far the most prevailing component amongst the catch composition of potentially aggressive species (Hazin et al. 2000). In spite of considerably low relative abundances, juvenile tiger sharks have been noted to occur off Recife in temporal clusters, with two or more individuals being caught in the same week or even in the same fishing set (F.H.V. Hazin et al., unpublished data). Even though the role of these smaller individuals in the shark attack problematic is not hitherto clear, it seems plausible that they may have been responsible for some of the incidents.

All tags popped-up over the continental shelf of northward regions, suggesting that juvenile tiger sharks preferentially move in the neritic zone off northeastern Brazil. This was sustained by the depth-temperature profiles registered by electronic tags, which evidenced a clear preference for superficial waters. Indeed, the observed vertical distribution may reflect a depth preference as much as a bathymetric constraint. The continental shelf off northeastern Brazil is relatively monotonous, slanting gently from the shoreline until a depth of about 50-60 m (Manso et al. 2003), where the slope abruptly starts. General maximum dive depths of 40-60 m observed in the greatest extent of all tracks suggest that juvenile tiger sharks in this region move mostly over the continental shelf, at least during the winter season when they appear to be more abundant off Recife (F.H.V. Hazin et al., unpublished data). The tagged individuals stayed most of the time at the mixed layer and so they were mainly exposed to a thermal niche of 24-28°C throughout the tracking period, as verified by temperature data. The lower temperature associated with T5 movements should be attributed not only to deep-diving behavior but also to seasonal variation in the water temperature, which usually tends to be minimum in August (Hazin et al. 2000). Interestingly, deeper dives into depths > 100 m were performed by all the three smaller individuals almost exclusively within the first ~13 days after tagging, with all sharks adopting a shallower vertical distribution after that period. The similarity of such pattern between different individuals suggests that it could be ascribed to post-release, stress-mediated behavior. It also suggests that tagged individuals seek refuge in offshore, deeper waters after being released. In fact, three of the sharks were clearly off the continental shelf within a 24 h period after being released. The duration of deep-diving pattern suggests that the behavior of caught-and-released juvenile tiger sharks could be altered during a couple of weeks after releasing, eventually implicating some behavioral biases during the beginning of telemetry studies. T2 was the only individual who did not exhibited such a propensity for escaping to deeper waters, which could be related to its larger size compared to the other specimens. The vertical distribution evidenced by these 4 tiger sharks is comparable with results obtained in Hawaii (Holland et al. 1999, 2001).

Observed minimum average speeds, measured by considering the shorter, soak distance between deployment and pop-up locations, were greatly different. T2 was the largest shark and appeared to move faster. However, the small duration of its track probably reduced the amount of biases imposed by both longitudinal and vertical movements, which would tend to diminish average speeds in longer tracks. In accordance, T2 minimum average speed was roughly comparable to tiger shark speeds assessed in previous studies. In Hawaii, an average speed of 0.29 body length per second ($BL.s^{-1}$) was measured for six acoustically tracked, mostly > 300 cm TL tiger sharks (Holland et al. 1999). Assuming 0.29 $BL.s^{-1}$ as a validated speed, the expected speed for T2 would be 0.57 $m.s^{-1}$, which is within the same order of magnitude of the measured speed (0.98 $km.h^{-1}$ = 0.27 $m.s^{-1}$). Such compatibility suggests T2 to have moved in a relatively well oriented latitudinal course, as opposed to longitudinal and/or vertical displacements, since T2 would already be expected to swim slower than > 300 cm TL individuals due to its smaller size. The pop-up latitudes of T1- and T3-tags were distinct, as well as the duration of their tracks. In spite of T3 having the longest track span (74 days), its location was the closest to the tagging site by the end of the tracking period, resulting in an unreasonable estimate of minimum average speed. On the other hand, T1 exhibited the highest latitudinal displacement by the end of its track (30 days), indicating that juvenile tiger sharks also utilize wide-ranging habitats off the continental shelf of northeastern Brazil. Despite the long distance achieved, the relatively low minimum average speed of T1 could be attributed to the more frequent longitudinal and vertical displacements when compared to the T2 shark. Tiger shark diel rhythmicity has been recorded in previous studies (Tricas et al. 1981), usually comprising predatory excursions to shallow habitats with high prey density to forage and subsequent returns to deeper waters (Heithaus et al. 2006, 2007, Lowe et al. 1996, 2006), although Meyer et al. (2009) found no evidence of rhythmic patterns of behavior in a more recent study. Off the Brazilian coast northward of Recife, such behavior would imply longitudinal movements which would necessarily reduce the rate of latitudinal displacement.

Tiger sharks visiting the littoral area of Recife during winter season appear to be performing northward movements at least on a regional scale. Whether tiger sharks approach Recife coming from eastern oceanic waters, following the South Equatorial Current, or coming from south, following the Brazilian coast, is a question that further satellite-tagging should clarify. In any case, if tiger sharks are being attracted shoreward by vessels approaching the Suape port, they might be expected to further move north into the littoral area of Recife. The probability of a tiger shark accessing into the risk area would then be a function of both bioecological features determining temporal variability of tiger shark abundance, and the intensity of maritime traffic to

Suape, which is variable at week- and year-level. Significant statistical correlations between periods of higher maritime traffic into Suape and shark attack events off Recife have been previously evidenced (Hazin et al. 2008), which further supports this hypothesis. Based on the assumption that the port of Suape is attracting sharks shoreward, the pattern of tiger shark regional movements suggested by the present study may possibly emerge as a significant factor contributing for the shark attack outbreak verified at Recife.

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RESUMO

A elevada taxa de ataques de tubarão verificada em Recife poderá estar relacionada com o comportamento migratório do tubarão tigre. O início desta situação coincidiu com a construção do porto de Suape localizado a Sul de Recife. Um estudo anterior sugeriu que algumas das espécies responsáveis pelos ataques poderiam estar seguindo as correntes costeiras para Norte e que o trânsito marítimo estaria atraindo as mesmas para junto da costa. Neste cenário, a movimentação dos tubarões para Norte implicaria uma maior probabilidade de estes acessarem o litoral de Recife após sairem de Suape. Para averiguar os padrões de movimentação do tubarão tigre no nordeste brasileiro, foram aplicados transmissores via satélite a 5 espécimes capturados ao largo de Recife. Todas as marcas transmitiram de latitudes a Norte após 7-74 dias em liberdade. A menor distância entre os locais de captura e de primeira transmissão foi de 33-209 km, correspondendo a velocidades médias mínimas entre 0.02-0.98 $km.h^{-1}$. As localizações da primeira transmissão e os dados de profundidade sugerem que os movimentos dos animais foram realizados principalmente sobre a plataforma continental. Os tubarões menores deslocaram-se para águas profundas em até 24 horas após a liberação, mas assumiram uma distribuição mais superficial (< 50 m) durante a maior parte do tempo. Este estudo apresenta os primeiros resultados das movimentações de tubarões tigre no Atlântico Sul e adiciona novas informações para a compreensão dos motivos que levaram à problemática de ataques de tubarão verificada nesta região.

Palavras-chave: migração, Recife, telemetria via satélite, ataque de tubarão, Suape.

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