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Diel Vertical Movements of a Scalloped Hammerhead, *Sphyrna lewini*, in the Northern Gulf of Mexico

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DIEL VERTICAL MOVEMENTS OF A SCALLOPED HAMMERHEAD, *SPHYRNA LEWINI*, IN THE NORTHERN GULF OF MEXICO

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ABSTRACT

Despite the circumglobal distribution of scalloped hammerheads, *Sphyrna lewini* (Griffith and Smith, 1834), little information is available regarding fine-scale movement and habitat use patterns for this species. Over a 27-d period, data were collected on diel habitat use and environmental preferences of a 240 cm (total length) female *S. lewini*. The shark exhibited a consistent and repeated diel vertical movement pattern, making more than 76 deep nighttime dives; the maximum depth reached was 964 m, where the temperature was 5.8 °C. The purpose of the nightly oscillatory deep diving pattern is unknown but could possibly represent feeding behavior. These findings represent the first detailed account of *S. lewini* diel vertical behavior and habitat utilization in the western North Atlantic Ocean.

The scalloped hammerhead, *Sphyrna lewini* (Griffith and Smith, 1834), is a large shark species that occurs worldwide in tropical, subtropical, and temperate marine waters (Compagno 1984). In the western North Atlantic Ocean, *S. lewini* occurs from New Jersey to Brazil, including the Caribbean Sea and Gulf of Mexico (GOM; Compagno 1984). In the northern GOM, *S. lewini* is distributed throughout the region in coastal and offshore waters (NMFS unpubl data); however, detailed knowledge of their ecology, behavior, and habitat requirements is limited. In June 2008, we opportunistically encountered a large school of *S. lewini* in offshore waters off the coast of Louisiana and were able to deploy a high-rate pop-up archival satellite tag (PSAT) on an adult female shark to describe its short term water depth and temperature preferences. We report the first account of diel vertical movements of *S. lewini* in the GOM.

Materials and Methods

On 19 June, 2008, a female *S. lewini* was caught using hook-and-line gear in surface waters adjacent to a petroleum platform (MC582) located in the Mississippi Canyon 60 km south of the Mississippi River Delta's Southwest Pass (Fig. 1). The platform is positioned in 678 m of water at 28.392°N and 89.454°W.

The shark was hooked and brought alongside the boat where it was sexed (female), measured (240 cm total length), and tagged with a high-rate PSAT (PTT-100HR, Microwave Telemetry, Inc.). The tag anchor was inserted into the shark's dorsal musculature at the base of the first dorsal fin. The tag was attached to an umbrella nylon dart anchor (1 × 3 mm; Domeier et al. 2005) with a 15.0-cm segment of 1.8-mm monofilament line that was wrapped with 3.2-mm marine grade heat shrink tubing. Following tag attachment, the hook was removed and the shark was released.

The PSAT measured 34.0 cm in length (including the 17.0 cm antenna), 1.6 cm in diameter at its widest point, and weighed 68 g in air. The PTT-100HR recorded and archived water

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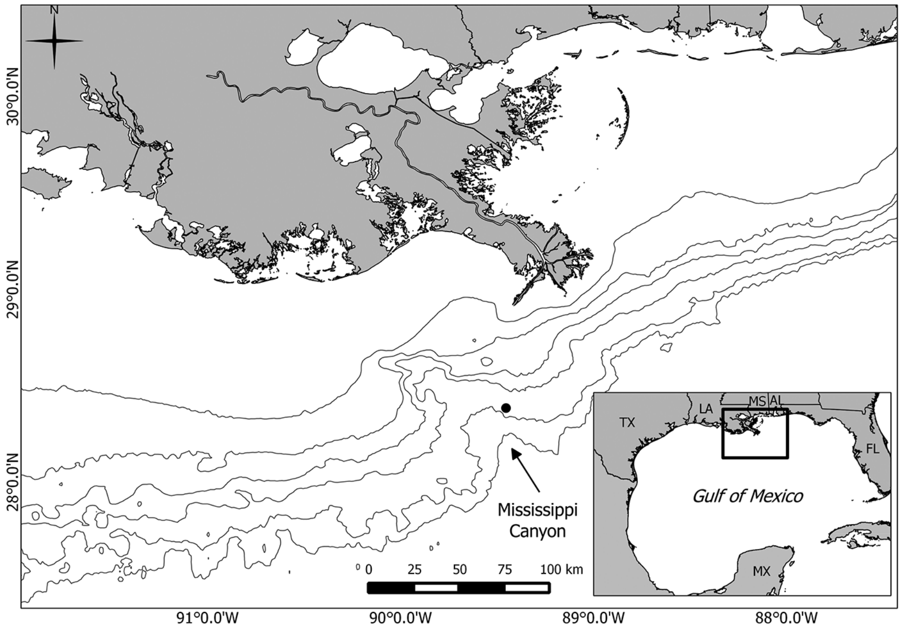

Figure 1. Map of the northern Gulf of Mexico showing the pop-up archival satellite tagging location (black circle) for the scalloped hammerhead, *Sphyrna lewini*. The 50, 100, 200, 400, 800, and 1000 m isobaths are indicated by black lines. The black circle represents the location of the petroleum platform, the tagging, and initial pop-up location, since all three occurred within 1.3 km of each other.

temperature (±0.2 °C) and pressure (depth; ±2.7 m) every 4 min. Due to battery limitations associated with increased resolution of temperature and depth data, the high-rate PSAT did not collect light-based geolocation data, so horizontal movements were not assessed. The tag was programmed to detach from the tether after 30 d, float to the surface, and upload archived data to the Argos satellite system.

For analytical purposes, depth and temperature measurements were stratified by daytime and nighttime using estimates of sunrise (06:05) and sunset (20:03) times at the tagging location calculated by the US Naval Observatory (http://aa.usno.navy.mil). Time-at-depth and time-at-temperature histograms were generated at 20-m (depth) and 2 °C (temperature) intervals and were separated by daytime and nighttime. The local mixed layer depth (MLD) was estimated using three CTD casts (Seabird SBE 911) conducted <50 km from the study site from July 13–16, 2008.

To examine diving behavior, individual dives were defined as vertical excursions that began in the mixed layer (<35 m), exceeded 300 m in depth, and were followed by a return to the mixed layer. Descent and ascent rates were also calculated. The descent phase of the dive began in surface waters (<35 m) and ended when the shark reached the maximum depth of the dive. The ascent phase began at the maximum depth of the dive and ended as the shark re-entered surface waters. If the dive was interrupted by multiple missing data points, then ascent and descent rates were not calculated. Mean rate of change (m s^{-1}) was calculated by dividing the depth difference by the time interval. Since the entire data set was not uploaded to the satellite, data points were grouped by hour and day and Pearson's chi-squared tests were used to determine if the missing values were evenly distributed throughout the data set. For statistical tests, results were considered significant at $P < 0.05$. Mean values are presented with standard error.

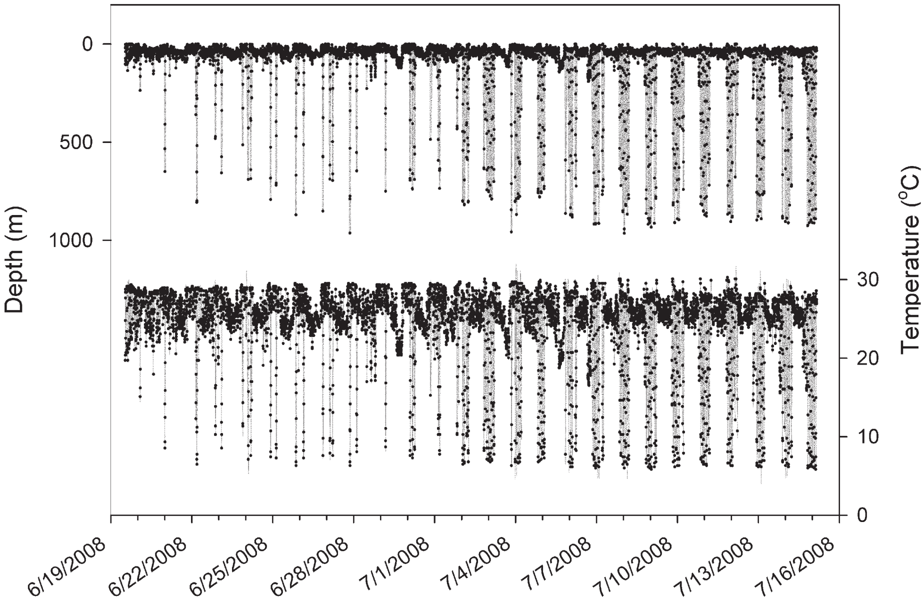

Figure 2. Measurements of depth and temperature recorded every 4 min during the 27-d pop-up archival satellite tag track of the scalloped hammerhead, *Sphryna lewini*.

Results

The PSAT detached from the shark on 15 July, 2008, "uplinked" to the Argos system, and transmitted archived data over a 21-d period. The tag was first detected by the Argos satellite system 1.3 km (0.83 nm) northeast of the deployment location at 09:38, 5.8 hrs after detachment. Only 20% of the data recorded by the tag was not recovered through the satellite and the missing data were evenly distributed among hours (chi-squared: $\chi^2_{23} = 26.7$, $P = 0.27$) and days (chi-squared: $\chi^2_{23} = 25.4$, $P = 0.38$).

Immediately following tagging on 19 June, 2008, the shark dove to 102 m and spent the remaining daylight hours between 20 and 60 m. During the duration of the tag deployment, the shark remained in relatively shallow waters (<60 m) during daytime and made multiple nightly dives to depths to 964 m (Figs. 2–3), which is well within the tag's maximum depth range of 1296 m.

Daytime depths ranged from 0 to 228 m, with the shark spending 83.4% of its time between 20 and 80 m. Nighttime depths ranged from 0 to 964 m, with the shark spending 71.7% of its time in surface/near-surface waters between 0 and 60 m, and 16.4% >241 m. The shark made more than 76 nighttime deep dives (>700 m), with 16 dives exceeding 900 m (Fig. 2–3) throughout the tag deployment. The MLD was estimated to be between 33 and 35 m. The shark spent its time as: 32.7% within and 67.3% below the MLD during daytime, and 60.3% within and 39.7% below the MLD during nighttime.

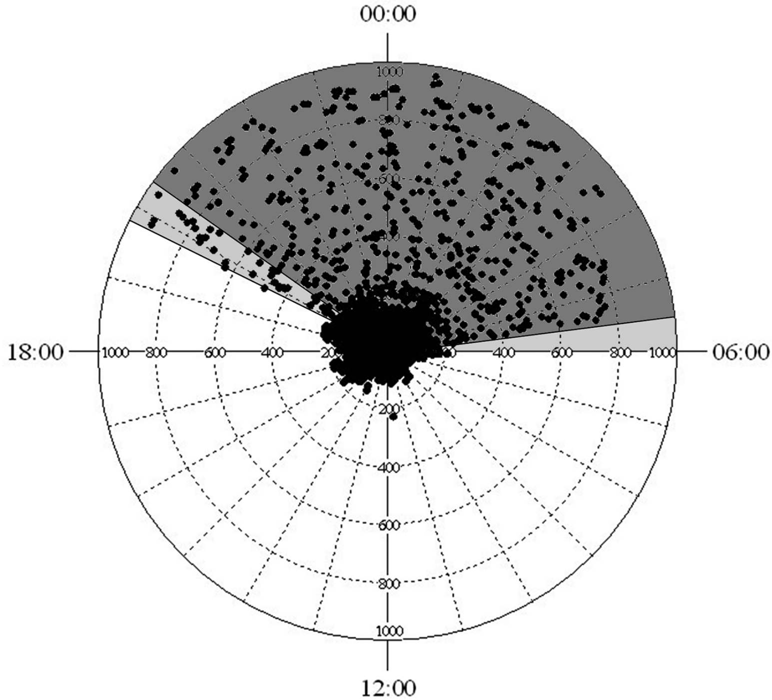

Figure 3. Circular-linear plot depicting depth distribution data recorded for the pop-up archival satellite tagged scalloped hammerhead, *Sphryna lewini*, over the 27-d of the study. Inner axes represent instantaneous depth (m) and the outer axis represents time of day (24 hrs). The light gray shaded area represents morning and evening civil twilight, whereas the dark gray shaded area represents nighttime.

Over the 27-d study period, the shark experienced water temperatures ranging from 5.8 to 30.3 °C (Fig. 2). Daytime temperatures ranged from 13.1 to 30.1 °C, with the shark spending 87.3% of the daytime at 23 to 28 °C. Nighttime temperatures ranged from 5.8 to 30.3 °C, with the shark spending 59.9% of the nighttime at 26 to 28 °C and 19.4% of the nighttime at <16 °C.

The mean number of deep dives per night was 4.2 (SE 0.49) with a mean duration of 41.6 (SE 1.4) min and a mean dive depth of 795.9 (SE 12.3) m. The mean estimated descent time and rate were 10.8 (SE 0.3) min and 1.31 (SE 0.03) m s^{-1}, and the mean estimated ascent time and rate was 26.9 (SE 0.6) min and 0.51 (SE 0.01) m s^{-1}. The approximate time at maximum depth for dives >700 m was 4 min. The surface/near-surface time interval spent between deep diving events ranged from 35 to 45 min [mean: 40.2 (SE 1.2) min]. Typically, the first descent each night began at dusk and the last ascent occurred just before sunrise [mean first descent time: 20:29 (SE 0:06), last ascent time: 04:53 (SE 0:15)].

Discussion

This study represents the first record of PSAT technology used to collect environmental preference and movement data for a *S. lewini* in the western North Atlantic.

Tag data revealed fine-scale vertical movements, including a pronounced diel vertical migration pattern within a larger vertical niche than was previously known for this species. Jorgensen et al. (2009) reported vertical movements of a PSAT-tagged *S. lewini* over a 74-d period in the Gulf of California that included four dives >900 m, which exceeded the previously known greatest depth (475 m) attained by this species (Klimley 1993). In our 27-d study, the PSAT-tagged shark made 76 nighttime dives >700 m in depth, 16 of which were >900 m, suggesting this is a common behavior for this species. However, tagging of additional individuals is required to verify the degree to which the observed behavior is common. Further, it should be noted that during the first 2 d after tagging, the shark showed limited vertical movements in the water column, which possibly represented a post-release behavior modification similar to what has been identified in other large pelagic fishes (Hoolihan et al. 2011).

The proximity of the PSAT's location to the MC582 platform shortly after its release from the shark suggests a possible affinity by the shark for the platform throughout tag deployment. Based on the depths of the dives, the shark most likely moved into adjacent, deeper waters of the Mississippi Canyon during nighttime and returned to the petroleum platform at dawn where it remained during daytime. Klimley et al. (1988) found that *S. lewini* aggregate at seamounts in the Gulf of California during daytime when no feeding was observed. Sharks then departed the seamount at dusk to forage in the surrounding pelagic environment and returned to the seamount by dawn on the following morning (Klimley and Nelson 1984, Klimley 1985, Klimley et al. 1988). If the shark tagged in the present study was using MC582 in a manner similar to conspecifics using seamounts in the Gulf of California, then petroleum platforms and salt domes in the GOM could provide similar function for *S. lewini*.

One of the most common behaviors of large pelagic fishes in the open ocean environment is oscillatory swimming, which could be related to energy conservation, behavioral thermoregulation, navigation, or feeding (West and Stevens 2001, Klimley et al. 2002). Weihs (1973) suggested that oscillatory swimming with a swim-glide mode of progression is a more efficient form of locomotion than straight line swimming and can serve as a means of "resting" or energy conservation. However, the dive profile of the tagged *S. lewini* revealed a "fast descent" and "slow ascent" profile, which has been reported for other shark species (Carey and Scharold 1990, Nakano et al. 2003, Cartamil et al. 2011) and is not consistent with the energy conservation hypothesis. Another proposed function of oscillatory swimming pattern observed in pelagic fishes is behavioral thermoregulation. The 40 min surface interval within the MLD consistently observed between deep diving events could have served as a "warming" period to recover from heat loss prior to the next dive into cold depths, and allowed the shark to maximize its time at depth, as suggested by Carey and Scharold (1990) for blue sharks.

The shark's nightly deep dives most likely represented feeding excursions targeting deep water prey, as suggested for other pelagic fishes exhibiting similar diving patterns (Holland et al. 1992, Schaefer and Fuller 2002, Wilson et al. 2005, Musyl et al. 2011). Although a deep oscillatory diving pattern was reported in *S. lewini* in other oceans (Klimley 1987, Klimley 1993, Jorgensen et al. 2009), none of these studies acquired high resolution data similar to what is presented here. The *S. lewini* in our study descended at a relatively high speed (up to 2.1 m s^{-1}) to a similar depth on each consecutive dive, suggesting that the shark was not feeding on its descent, but most likely while on the bottom or during ascent. The shark could have been feeding on benthic prey items such as deep water batoids, which are known to occur in the diet of *S. lewini* in the northern GOM (E Hoffmayer, unpubl data). Further evidence for deep diving feeding behavior is found in dietary studies of *S. lewini* that report a high incidence of mesopelagic teleosts, mesopelagic cephalopods, and deep water crustaceans (Klimley 1987, Stevens and Lyle 1989, Smale and Cliff 1998, Júnior et al. 2009).

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