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Horizontal and Vertical Movements of the Shortfin Mako Shark, *Isurus oxyrinchus*, in the Southern California Bight

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Abstract

Recreational and commercial fishing effort directed at the shortfin mako shark, *Isurus oxyrinchus*, off the coast of southern California increased markedly in the mid 1980s. However, very little is known about the population size, stock structure or movements of these sharks in the northern Pacific. It is important to determine their role in these waters because the southern California bight may be an important pupping and nursery area for shortfin mako sharks.

Acoustic telemetry was used to identify short-term horizontal and vertical movements of three shortfin mako sharks in the southern California bight during the summer of 1989. All three sharks were two-year-old juveniles and were tracked for periods of from 18 to 25 h. They spent 90% of their time in the mixed layer, with only infrequent excursions below the thermocline. Vertical and horizontal movements did not indicate any diel activity pattern associated with distance to the shore or nearby islands or with bottom topography.

Extra keywords: tagging, tracking, water temperature.

Introduction

Recreational and commercial fishing effort directed at the shortfin mako shark, *Isurus oxyrinchus*, off the coast of southern California increased markedly during the 1980s (Holts 1988). Popular interest in the shortfin mako shark as a sportfish and consumer acceptance of it as a commercial foodfish encouraged continued harvests. Popularity with sportfishers on both chartered sportfishing vessels and private boats has increased by an order of magnitude in recent years. Estimated fishing effort in angler trips (number of individual angler fishing trips) increased from 41 000 in 1986 to more than 410 000 in 1989 and may still be increasing (S. Crook, California Dept. of Fish and Game, personal communication). Approximately 90 to 180 t (metric tonnes dressed weight) of shortfin mako sharks are taken commercially as an incidental catch in the Californian drift-net fisheries for thresher sharks, *Alopias vulpinus*, and swordfish, *Xiphias gladius* (Bedford and Hagerman 1983; Holts 1988; Hanan *et al.* 1993). An experimental longline fishery targeting shortfin mako sharks began off southern California in 1988 and continued through the 1991 fishing season. An additional 68 t of shortfin mako sharks were landed annually in this fishery. Total commercial landings of shortfin mako sharks for all southern Californian coastal fisheries exceeds 200 t annually. This has raised concerns about the ability of the resource to sustain the current level of fishing pressure. Very little is known about the population size, stock structure, distribution or movements of the shortfin mako shark off the US Pacific coastal states. Catch records from the California Department of Fish and Game indicate that the fisheries take shortfin mako sharks primarily within 93 km of shore and from the California–Mexico border to as far north as San Francisco. They are available in greatest abundance in the spring and summer months; catches are greatest between June and August.

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The catch is composed almost entirely of juvenile 1- and 2-year-old fish weighing from 13·6 to 27·2 kg (Hanan *et al.* 1993). The southern California bight may serve as a nursery area for newborn and juvenile shortfin mako sharks (Holts and Bedford 1989).

Shortfin mako sharks grow slowly, mature relatively late in life, and have a long gestation period (Pratt and Casey 1983). They produce a few (generally 4 to 16) well developed pups (Stevens 1983) whose survival is assumed to be good because of their advanced development at birth. This life-history strategy makes these sharks quite vulnerable to modern commercial and recreational fishing operations.

Information on distribution and short- and long-term movement patterns is necessary in assessing the status of affected stocks and in determining management options should management of coastal shark fisheries become prudent. Conventional dart-tagging studies in the north-western Atlantic have yielded considerable information concerning long-term movements of shortfin mako sharks in that area (Casey and Kohler 1992), but studies conducted off the southern Californian coast have only begun to reveal long-term movements of shortfin mako sharks there. Still less is known about the short-term behaviour of individuals. Acoustic telemetry has proved to be useful in identifying the short-term horizontal and vertical movements of several shark species (Carey 1990; Carey and Scharold 1990; Nelson 1990) and other large pelagic fish species (Carey and Robison 1981; Holland *et al.* 1990*a*, 1990*b*; Holts and Bedford 1990; Brill *et al.* 1993).

During the summer of 1989, four five-day cruises were conducted through a cooperative agreement between the Southwest Fisheries Science Center and the California Department of Fish and Game. The primary objective was to determine short-term movements and activity patterns of shortfin mako sharks in the waters off southern California by using acoustic telemetry.

Materials and Methods

The 18-m sportfishing vessel *Pacific Clipper* was chartered from 14 August to 15 September 1989. The acoustic tracking techniques and equipment used in this study were identical to those previously described for tracking striped marlin (Holts and Bedford 1990). This involved the use of a hull-mounted directional hydrophone and ultrasonic receiver (Vemco[1] CS40 and VR60, respectively) to indicate direction and approximate distance to the tagged shark. The acoustic transmitter tags (Vemco[1] V4P) had working pressures of 100 psi and 500 psi (working depths of 0 to 70 m and 0 to 340 m, respectively). The tracking vessel remained within 400 m of the fish, and loran-C coordinates were recorded every 15 min for horizontal positioning. Temperature profiles of the water column were measured with expendable bathythermographs approximately every 6 h.

Sharks were captured by rod and reel. Terminal tackle consisted of a 5-m length of leader constructed from braided wire (250-pound test) and a size '9/0' hook baited with Pacific mackerel, *Scomber japonicus*, or Pacific sardine, *Sardinops sagax*. Sharks were attracted to the vessel by chumming with finely chopped mackerel. Of 28 shortfin mako sharks captured, only the three largest were selected for tagging with acoustic transmitters. To minimize capture trauma, these sharks were quickly brought alongside the boat, where the transmitters were attached with a hand-held harpoon applicator without removing the sharks from the water. They were then released by cutting the leader as close to the hook as possible. Tracking commenced immediately after each fish was released. Total length and weight were estimated while the fish was being tagged.

Results

All three sharks were tagged and tracked off Oceanside, California, in the channel formed by Santa Catalina and San Clemente Islands (Fig. 1). Tracking periods ranged from

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service.

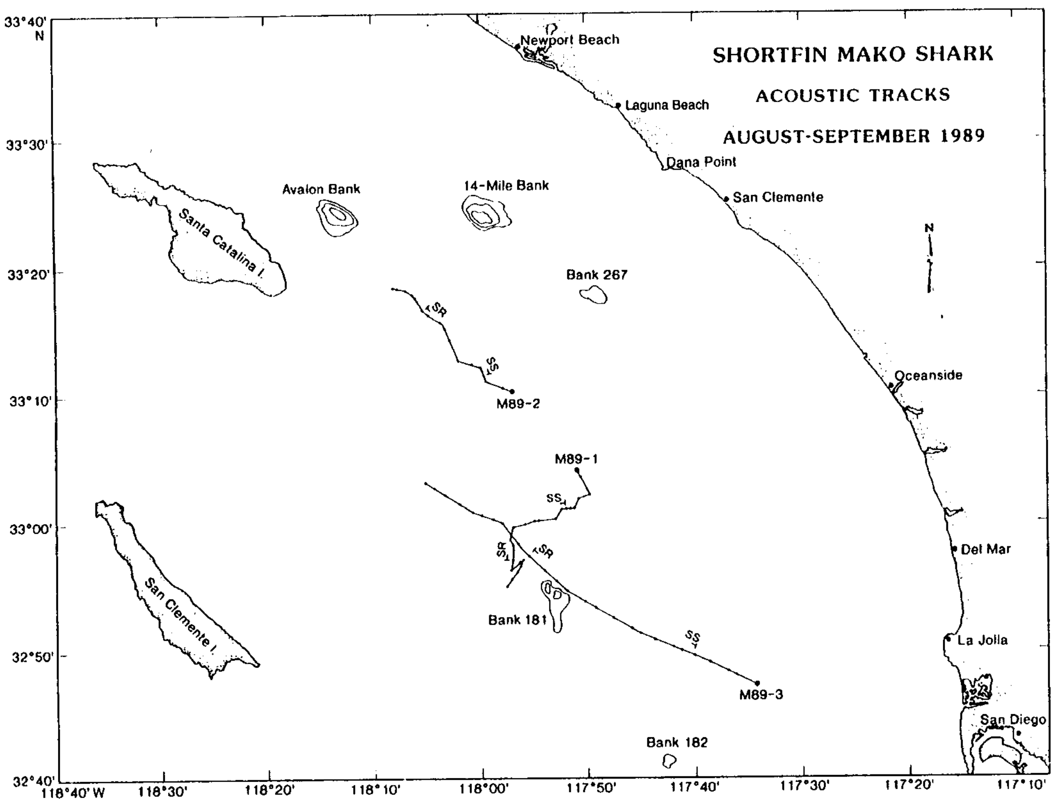

Fig. 1. Horizontal movements of three shortfin mako sharks acoustically tracked in the southern California bight, August–September 1989. SR, sunrise; SS, sunset.

18 to 25 h and covered 24 to 57 km. Data for both horizontal movements and vertical depth variations were obtained for all tracks. The location of the shark was assumed to be the same as that of the tracking vessel. Loran-C positions recorded every 15 min were smoothed with a running average over 90-min periods to indicate rate of movement.

The first shortfin mako shark tracked (Shark M89-1) was estimated to be a 1·8-m, 36-kg female and was tagged at 1300 hours on 15 August 1989. It was released 18 km north of the '181 Fathom Bank' (at 33°06'N,117°52'W), and it moved 30 km in a generally southerly direction over the next 25 h (Fig. 1). The overall rate of movement was 1·10 km h^{-1} (Fig. 2). Speed decreased from about 2·0 km h^{-1} after release to less than 0·74 km h^{-1} just before sunset, then increased markedly to 2·78 km h^{-1} at 2030 hours. Speed gradually declined during the remainder of the night to 0·74 km h^{-1} just after sunrise. Between sunrise and the end of the track, this fish again increased its speed to about 1·80 km h^{-1}.

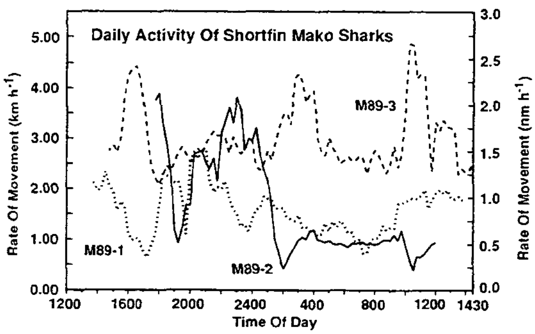

Fig. 2. Daily activity, in kilometres per hour and nautical miles per hour, for three shortfin mako sharks tracked in the southern California bight, August–September 1989.

This shark initially sounded to 35 m but slowly ascended over the next 45 min to about 7 m, where it remained until 1630 hours (Fig. 3). Between 1630 and 2000 hours, it made

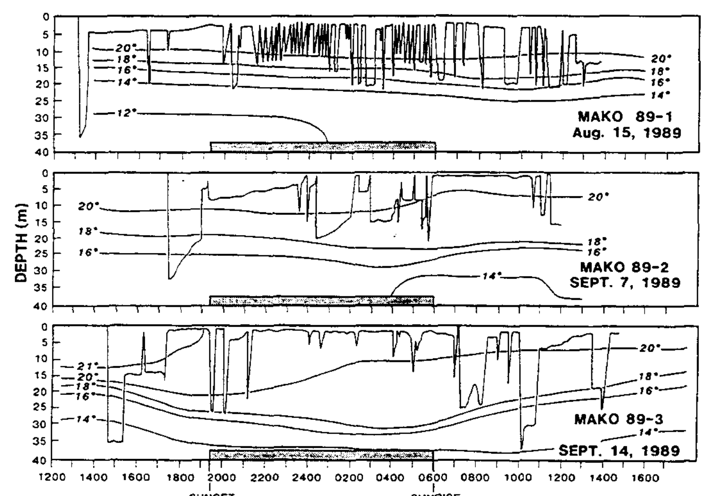

Fig. 3. Diving profiles for three shortfin mako sharks in the southern California bight, August–September 1989. Temperatures shown in °C.

two short-duration dives, returning each time to a depth of 4 to 5 m. Sunset occurred at 1930 hours, and the shark began making numerous, almost rhythmic, dives between 3 and 20 m. This pattern continued until sunrise and totalled 32 dives, or an average of 3·5 dives h^{-1}. The deepest and longest of these was to 21 m for 23 min at 0300 hours. Dive frequency decreased to less than 2 dives h^{-1} soon after sunrise. This shark spent little time below the steepest gradient of the thermocline.

The second shark tracked (Shark M89-2) was a 1·7-m individual estimated to weigh 32 kg. Its sex was not determined. Tagging and release occurred 30 km north of the '181 Fathom Bank' (i.e. at 32°54'N,117°53'W) at 1730 hours on 7 September 1989 (Fig. 1). This shark travelled 24 km north-west in 18 h and averaged 1·29 km h^{-1} during the daylight hours and 1·48 km h^{-1} at night. As with Shark M89-1, speed decreased from a post-release high of 3·7 km h^{-1} to less than 0·92 km h^{-1} just after sunset. Speed then increased through midnight but decreased to about 0·92 kn h^{-1} for the remainder of the track (Fig. 2). Prior scheduling required the tracking of Shark M89-2 to be terminated after only 18 h.

After release, this second shark immediately descended to 33 m, where it remained for 90 min before gradually ascending to 20 m (Fig. 2). At 1900 hours, just before sunset, it ascended quickly to about 5 m, where it remained until 2000 hours. It remained above 10 m until about midnight, when it descended to 29 m and slowly rose to 12 m over the next couple of hours. A series of short dives followed until sunrise, when the frequency and depth of dives decreased. Shortly after sunrise, it positioned itself between 2 and 4 m, where it remained for the next 4 h. Another series of short dives commenced at 1030 hours. These dives may have been influenced by our attempts to position the tracking boat in the path of the fish in an unsuccessful effort to recapture this individual. The top of the thermocline varied between 18 and 22 m in depth during this track, but the shark did not descend into it except for the initial plunge.

The third shark tracked (Shark M89-3), a 1·8-m, 32-kg individual, was tagged at 1430 hours on 14 September 1989. Sex was not determined. This fish was tagged 31 km east of the '181 Fathom Bank' (i.e. at 32°47'N,117°34'W), and it moved west-north-west, passing over a shoal area near the '181 Fathom Bank' and covering 57 km during the 24-h tracking period (Fig. 1). This shark differed from the other two by covering nearly twice the distance and averaging 2·40 km h^{-1} (Fig. 2). The speed of this shark increased to more than 4·44 km h^{-1} during the first 3 h of the track and then decreased to almost 2·0 km h^{-1}. Speed then remained at about 2·40 to 2·77 km h^{-1} for most of the remainder of the track, with noticeable increases at 0200 and 1000 hours.

When released, Shark M89-3 also sounded to 33 m. Within 1 h it ascended to 15 m, where it remained until 1715 hours (Fig. 3). It then rose to within 1 m of the surface. Just after sunset, it made three dives to 20–25 m. It remained within 3 m of the surface during the night. After sunrise, it descended to 22 m for about 1 h before rising to near the surface. Its deepest dive to 33 m occurred at 1000 hours. This dive and a final one to 19 m at 1300 hours each lasted about 1 h and were well into the upper portion of the thermocline.

Discussion

Post-tagging Dive and Survival

All three shortfin mako sharks were released in good condition and showed no apparent harmful effects from being tagged throughout the tracking period. There was no apparent trauma from capture extending beyond the post-tagging dive.

Vertical dive profiles indicate that the trauma of capture and release may last only 30 to 90 min. Horizontal movements of Sharks M89-1 and M89-2 support this observation. The actual speed of these two sharks decreased substantially within 2 h of release. The third shark (M89-3) increased its speed over the first 2 h while it remained at a depth of 30 m, then slowed as it ascended into the mixed layer.

An initial dive into the cooler waters below the thermocline immediately following release has been noted for blue sharks, *Prionace glauca*, by Sciarrotta and Nelson (1977), Tricas (1979) and Nelson (1990) and for billfish by Holland *et al.* (1990*a*) and Holts and Bedford (1990). This may be a response of obligate ram ventilators to overcome an oxygen debt built up during capture, as suggested by Holland *et al.* (1990*a*). This is certainly possible in the present case because shortfin mako sharks are active fish when caught on sportfishing gear and undoubtedly expend considerable energy attempting to escape. Both muscular and visceral temperatures in the shortfin mako shark are maintained well above ambient water temperature through a system of vascular counter-current heat exchangers (Carey *et al.* 1981, 1985). The time spent in these post-tagging dives may also be a behavioural response to regulate internal temperature by dissipating excess heat built up during the catching and tagging process.

Horizontal Movements in the Southern California Bight

The southern California bight has a diverse topography that includes several large islands ranging in distance from 20 to 110 km from the Californian shore. The average water depth is 700 to 1000 m in the immediate tracking area, although numerous submarine escarpments and banks rise to within 100 m of the surface. The southern California bight is also influenced by the California Current and counter-current, which forms many eddies in and around the islands. These currents and resulting eddies probably influenced the movement of the sharks we tracked. Water currents were found to influence the movement of striped marlin off the island of Hawaii (Brill *et al.* 1993). Unfortunately, the measurement of water currents and eddies requires current-profiling systems not available on small tracking vessels.

All three tracks in this study began and ended within a few kilometres of various submarine features within the southern California bight. However, there was no clear indication that any of the sharks tracked were actually associated with these features. Each capture and tagging location was influenced by drift because our 'chumming line' extended over several kilometres at times.

Shark M89-1, although moving generally south, varied its direction considerably more than did Sharks M89-2 and M89-3. These last two sharks both travelled in a fairly direct westerly direction. Sharks M89-1 and M89-2 averaged $1\cdot33$ km h^{-1} over the tracking period (Fig. 3). Shark M89-3 travelled nearly twice as far as the others, averaging $2\cdot55$ km h^{-1}. The rate of movement in the first hour of tracking exceeded $1\cdot80$ km h^{-1} for all three fish. M89-1 and M89-2 both slowed considerably in the first few hours after release, whereas M89-3 first increased its speed to nearly $4\cdot44$ km h^{-1} before slowing to $2\cdot77$ km h^{-1}. The average rate of movement for all three fish was lowest during the early to mid-morning hours. One shortfin mako shark (about the same size as our fish) tracked off the eastern coast of the USA averaged about $3\cdot70$ km h^{-1} without any apparent change in swimming pattern, although it did reach $5\cdot55$ km h^{-1} for a short time (F. Carey, personal communication). White sharks, *Carcharodon carcharias*, tracked off southern Australia averaged $3\cdot2$ km h^{-1} (Strong *et al.* 1992).

Satellite images of sea surface temperatures (SSTs) were obtained for each track. Several temperature breaks and current eddies of 1°C to 2°C were present in and around the islands of the southern California bight. The SST image associated with the track of Shark M89-1 was obscured by clouds. The track of Shark M89-2 stayed on the warm side of a 2°C temperature break as the fish moved west toward the Avalon Bank. The track of Shark M89-3 crossed two temperature gradients as the fish moved from warmer water off La Jolla, California, to water 2°C to 3°C cooler as it moved west. Neither of these two sharks showed any sign of changing their behaviour in response to SSTs as did the striped marlin tracked earlier in the same area (Holts and Bedford 1990).

Vertical Distribution and Temperature Preferences

A major feature of this study is that the three juvenile shortfin mako sharks observed in the southern California bight oriented to the surface waters above the thermocline. They spent 90% of the total tracking time in the mixed layer above 20 m. Slightly more daylight hours than night-time hours were spent below 20 m (Fig. 3).

The track of Shark M89-1 showed considerably more vertical activity than did the tracks of the other two sharks. M89-1 spent most of the night-time hours in continual vertical excursions between 2 and 15 m. The frequency of excursions slowed considerably after sunrise, although activity remained high through the end of the tracking period. Tracks from M89-2 and M89-3 showed fewer vertical excursions, but several of these lasted 1 h or longer. Vertical excursions of M89-1 and M89-2 were greatest during the night, whereas M89-3 was most active during the mid-morning period of the second day. These sharks did not descend below 25 m during the night-time hours, and, excluding the post-tagging plunge, only one (M89-3) descended below 25 m during the day.

Depth of the thermocline averaged 14–16 m during the first track and 19 to 20 m during the second and third. In all tracks, the mixed layer was 20°C to 21°C and the steepest gradient in the thermocline occurred from 18°C to 20°C. The total time that all three sharks spent in the mixed layer was 81·6%, with another 11·4% spent in the 18°C to 20°C transition zone (Table 1). Only infrequent or short excursions below the thermocline occurred, and there was little difference between day and night. Only vaguely apparent in this study were patterns observed for blue and shortfin mako sharks in the Atlantic. Those sharks made their longest excursions and deeper dives during the day and smaller vertical excursions at night. In that study, a large female shortfin mako shark spent most of the time well below the mixed layer and reached depths greater than 400 m several times (Carey and Scharold 1990). Our sharks were smaller than the shortfin mako and blue sharks tracked by Carey and Scharold (1990). The reason for observed differences in depth preference is unknown, although condition, age and location may all be involved.

Several other pelagic predators prefer the warmer water of the mixed layer, including the blue shark (Sciarrotta and Nelson 1977) and the striped marlin (Holts and Bedford 1990). Still others, including the white shark (Carey *et al.* 1982) and the yellowfin tuna, *Thunnus albacares* (Carey and Olson 1982; Yonemori 1982), orient to the steepest gradient of the thermocline.

Table 1. Percentages of time spent at different temperatures during day (D) and night (N) for shortfin mako sharks

Temperature (°C)	Shark M89-1		Shark M89-2		Shark M89-3		Combined		Total
	D	N	D	N	D	N	D	N	
20–21 (mixed layer)	75·4	86·3	65·3	79·8	74·3	100·0	73·3	88·4	81·6
18–19	9·9	10·6	22·1	20·2	10·8	–	12·3	10·3	11·4
17–18	1·3	1·2	5·9	–	0·6	–	1·8	0·5	0·6
16–17	4·8	0·8	6·5	–	5·6	–	5·3	0·3	2·8
15–16	2·3	0·7	0·2	–	0·9	–	1·4	0·3	0·3
14–15	3·0	0·4	–	–	0·8	–	1·6	0·2	0·9
13–14	1·5	–	–	–	7·0	–	3·4	–	1·7
12–13	1·8	–	–	–	–	–	0·9	–	0·7

Diel Patterns

Neither horizontal nor vertical movements indicated any diel activity pattern common to all three sharks. Likewise, no pattern of movement such as a home range associated with the nearby islands, the banks or the shore was evident, probably owing to the diverse topography in the area. Sciarrotta and Nelson (1977) observed an island-oriented onshore–offshore movement in blue sharks associated with feeding. Interisland cruising and island patrolling were described for white sharks (Strong *et al.* 1992). The shortfin mako sharks tracked in the present study were not obviously orienting to any features. At this age, in the southern California bight, juvenile shortfin mako sharks may have an extensive home range as do shortfin mako sharks in the Atlantic (Casey and Kohler 1992). If this is the case, extended tracks of several days may be necessary to identify any diel activity patterns or island-oriented movements.

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