Use of pop-up satellite archival tags to demonstrate survival of blue marlin (*Makaira nigricans*) released from pelagic longline gear

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Blue marlin (*Makaira nigricans*) support commercial and recreational fisheries throughout the tropical and subtropical waters of the Atlantic Ocean. The species is taken in directed recreational and artisanal fisheries in several areas and constitutes an incidental catch of the widespread commercial pelagic longline fishery. Although blue marlin comprise only a small fraction of the catch of the pelagic longline fishery that targets tunas and swordfish, this fishery accounts for the majority of fishing mortality on Atlantic blue marlin (ICCAT, 1997; 2001).

Atlantic blue marlin were last assessed in 2000 by the Standing Committee for Research and Statistics (SCRS) of the International Commission for the Conservation of Atlantic Tunas (ICCAT). The assessment indicated that the total biomass of Atlantic blue marlin is only about 40% of that necessary to produce maximum sustainable yield (MSY) and that current harvests are more than twice the replacement yield, further contributing to the decline of the stock (ICCAT, 2001). A reduction in fishing mortality of approximately 60% is needed simply to halt the decline in stock abundance (Goodyear, 2000).

One means of reducing fishing mortality on blue marlin, without severely impacting catches of target species of the pelagic longline fishery, is to release those blue marlin that are alive at the time longline gear is retrieved (hauled back). Jackson and Farber (1998) reported that 48% of blue marlin caught in the Venezuelan longline fishery are alive at the time of haulback. Data from the U.S. observer program between 1992 and 1996 indicate that 66% of blue marlin were released alive from the domestic longline fishery (Lee and Brown, 1998) and U.S. National Marine Fisheries Service (NMFS) data and mandatory pelagic longline logbook submissions between 1987 and 1991 indicate that 59.8% of blue marlin are released alive from commercial pelagic longline gear (Cramer, 1998).

ICCAT has been encouraging the release of live blue marlin for several years, and in 2000 the Commission mandated that all live blue marlin and white marlin be released from commercial longline and purse seine vessels. However, for such a management measure to significantly reduce fishing mortality, released animals must have a reasonably high postrelease survival rate.

Little information exists about postrelease survival of blue marlin, especially of animals taken on pelagic longline gear. In general, recovery rates of billfish tagged with conventional (streamer) tags have been quite low (<2%; Jones and Prince, 1998; Ortiz et al., 1998). This observation is consistent with high postrelease mortality, although low recovery rates could also result from tag shedding and a lack of reporting recovered tags (Bayley and Prince, 1994; Jones and Prince, 1998). Results of acoustic tracking studies of blue marlin captured on recreational gear suggest that postrelease survival over periods of a few hours to a few days is relatively high, although mortalities have been noted (reviewed in Pepperell and Davis, 1999). More recently, pop-up satellite archival tags (PSATs) have been used to study postrelease survival of blue marlin taken in a recreational fishery. Graves et al. (2002) attached nine PSATs to blue marlin caught on recreational gear off Bermuda. Eight of the tags detached from the animals and reported as expected after five days; net displacement and direction, tag inclination, and temperature data for all eight individuals were consistent with postrelease survival for five days.

In this note, we present the results of a study evaluating the postrelease survival of blue marlin from pelagic longline fishing gear in the western North Atlantic. We include analyses of the movement and behavior of these animals for tagging periods of both five days and thirty days.

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Materials and methods

Pop-up satellite tags

There has been rapid development in PSAT technology over the past few years, and there are currently several PSAT models commercially available from different vendors. PSATs vary in many features: in the number of functions (temperature, pressure, tag inclination, light level) they measure; in the parameters and release time for which they can be programed; in the onboard data that they can manipulate and store, in the data they transmit, in their emergency release mechanisms or emergency programming (or both), and in their cost. PSATs have been used on several large pelagic teleosts, including North Atlantic bluefin tuna (e.g. Block et al., 1998; Lutcavage et al., 1999), swordfish (Sedberry and Loefer, 2001), and blue marlin (Graves et al., 2002).

The two tag models used to evaluate postrelease survival of blue marlin in this study—the Microwave Telemetry Inc. (Columbia, MD) PTT-100 (5-day tag) and the Wildlife Computers (Redmond, WA) PAT (30-day tag), are similar in external appearance. Both are slightly buoyant, measure approximately 38 cm by 4 cm diameter (including antenna) and weigh between 65 and 75 g (air weight minus attachment leader and tag head). The size of these tags is sufficiently small as to not appear to impose a major drag on a large marine teleost such as a blue marlin (Block et al., 1998). The greatest exterior differences between the two tag types are their color (the 5-day tags are black and the 30-day tags are grey and white) and the presence of a small metal emergency release mechanism on the attachment leader of the 30-day tag. Both tag models can withstand a minimum pressure equivalent to a depth of about 1000 meters, which is well below the maximum observed depth of previous acoustic tracking analyses of blue marlin movements (Holland et al., 1990; Block et al., 1992).

The 5-day tags (n=7; described in this paper as 5D-1 through 5D-7) were programmed by the manufacturer to detach from the fish 122 hours after activation. A release time of five days was chosen for this PSAT because several blue marlin tagged with conventional tags have been recaptured within five days, demonstrating a return to feeding behavior (E. Prince, unpubl. data). Moreover, mortalities of released blue marlin that have been observed with acoustic telemetry have occurred within 48 hours of release (Pepperell and Davis, 1999). The 5-day tags measured water temperature once an hour and stored the average of two hourly values, for a total of 61 temperature means (from 122 measurements).

The 5-day tags also reported two average inclinometer values, one before the tag released from the fish and one after. These values can be used to infer active forward movement by the fish. This instrument measures the percentage of deployment time that the tag was at an attitude of less than 30° above horizontal by taking a reading every two minutes and either adding or subtracting this percentage from the running total value. Because this value is bracketed with maximum (255) and minimum (0) boundaries, and measurements are taken at short-duration intervals, a mortality or tag shedding event displaying a lack of forward movement will show clearly as an almost vertical reading, even if the fish was initially quite active.

The 30-day tags (n=2; described within this paper as 30D-1 and 30D-2) were programmed by the user to release 32 days following deployment, allowing for a full 30 days of data collection. The release time for the 30-day tags was chosen, in part, to test the assumption that five days was a sufficient duration to capture the rate of postrelease mortality resulting from interaction with longline gear, and to obtain more detailed behavioral data over a longer time interval. It should be noted, however, that a longer release time may bias estimates of postrelease survival because there is an increased period for tag malfunction, physical damage to the tag, or other sources of mortality to occur (Goodyear, 2002). Using the manufacturer's software (PatHost programming software, version 2.06, Wildlife Computers) the 30-day tag was programmed to record temperature values (sensitivity=0.05°C) every minute, and the data were collated for transmission as the fraction of time during each hour-long period that the tag was within each of 12 user-defined bins between the following temperatures (°C): ≤5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30, and 60 (for 30D-1) and ≤7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, 30, 32.5, and 60 (for 30D-2). Similarly, direct pressure measurements (measured sensitivity=0.5 m) were taken every minute and collated for transmission as the percentage of time during each hour that the tag was within each of 12 user-defined categories between the following depths (m): <0, 2.5, 5, 10, 15, 25, 50, 100, 250, 500, 750, and 1000 (30D-1 and 30D-2). These two tags also recorded minimum and maximum depths and temperatures for each hour during deployment. Finally, the tags recorded light level measurements every minute, and these data were used to calculate a local time of midnight and duration of daylight, thereby allowing a later estimate of daily position.

Analyses

The slightly buoyant tags detached from the fish after the specified intervals, floated to the surface, and transmitted archived data to satellites in the Argos satellite system. Position information and sections of stored data were captured with each satellite pass (Arnold and Dewar, 2001), transmitted to a ground station, and ultimately to the authors by means of the Internet. Location data were analyzed by using the computer program PROGRAM INVERSE (version 2.0, National Geological Survey, 1975; modified by M. Ortiz, NMFS Southeast Fisheries Science Center, Miami, FL) to determine net direction and minimum net displacement from the point at which the blue marlin was tagged and released to the position of the tag at the time of the first precise position (location code 1, 2, or 3) determined by the Argos satellite system. Temperature data from the 5-day tags deployed off Florida were categorized by time of collection as daylight, nighttime, or a composite dawn and dusk period (one hour before and after sunrise and one hour before and after sunset), for analysis of temperature by light level using a one-way ANOVA (Zar, 1999).

Tag deployment

Four commercial longline vessels (48–70 feet LOA [length overall]) in the western North Atlantic Ocean were used for the present study. All carried approximately 20 miles of longline on one large spool, centrally mounted amidships. Gear was set off the stern and retrieved from a hauling station located on one side, approximately amidships—a standard vessel configuration for the U.S. Gulf of Mexico and east coast swordfish fleet. Fishing gear was also typical for vessels in this fleet. A mainline of single-strand monofilament was used and a variety of terminal gear configurations. Different lengths of dropper lines or numbers of hooks between floats (or both) were used in attempts by captains to increase billfish catch rates, although all modifications to the gear were within the range of terminal gear configurations used in this pelagic longline fishery. Leader lengths ranged from 5 to 20 fathoms (9.2–36.6 m), and the buoy drops generally were 10 to 15 fathoms (18.3–27.5 m). Vessels in this study used a combination of "J" hooks (8/0–9/0 sizes) and circle hooks (16/0 size). Bait was either mackerel (Scomber sp.) or squid (*Illex* sp.), and almost every set used chemical lightsticks of varying colors attached to the leader approximately 2 meters above the hook.

PSATs were prepared for attachment to blue marlin prior to departure of the vessels. A large, hydroscopic, surgical-grade nylon tag head was attached to the PSAT with an approximately 20 cm length of 300-pound-test Momoi® brand (Momoi Fishing Co., Ako City, Japan) monofilament line. Metal crimps, covered with black heat-shrink tubing to minimize potential abrasion along the fish's body, were used to attach the monofilament line to the PSAT and the tag head. Individual PSATs were activated and tested at the start of each fishing day prior to the morning haulback. The white flotation bulbs of the 30-day tags were colored black with a permanent marker prior to deployment to decrease their visibility while attached to the fish.

PSATs were attached to all blue marlin that were caught on commercial pelagic longline gear, weighed more than approximately 100 pounds (45.0 kg), and were observed to be in relatively good physical condition, e.g. no large wounds to the viscera. Of the ten blue marlin caught during this study, all but one passed this minimum standard (the one fish that was rejected arrived at the side of the vessel missing the posterior half of its body due to several large bites). Fish were brought alongside the vessels just aft of the hauling station along the rail prior to tagging. Several fish required up to two minutes to become calm enough to be tagged accurately. Many longline captains attempt to save as much leader material as possible from bycatch fishes, and bringing a fish close to the vessel prior to cutting the line is a common practice. The FV *Ark Angel* had a removable section of rail that facilitated tag attachment; on the other three vessels one was forced to lean out over a rail to attach a tag. The average distance between the top of the rail and the fish (freeboard) was approximately one meter. The PSAT tag head was carefully inserted about 5–10 cm below (ventral) the midpoint of the anterior dorsal fin. Tag heads were implanted to a depth of about 8 cm by using a modified tagging applicator approximately 2 meters in length. A conventional streamer tag was attached well posterior of the PSAT by using a standard tagging applicator. Total tagging time, from identification of the fish on the leader as a blue marlin to release following tagging, was less than 5 minutes per fish.

Blue marlin were released by the standard commercial release protocol of cutting the leader near the hook and allowing the hook to remain in the fish. Approximate weights were estimated, and physical location of the hook noted for each blue marlin. An "ACESS" condition scale, analogous to the human neo-natal APGAR test (Apgar, 1953), was developed to quickly evaluate the condition of each fish on a scale of 0–10 by examining five characteristics and assigning each a score of 0–2 (poor to good). These characteristics included overall activity, color, condition of the eyes, stomach eversion, and the general state of the body musculature (presence of bites or lacerations). The time of day, vessel location, and surface water temperature were recorded immediately after tagging. The location of a hooked fish on the longline was also noted in order to estimate the "soak time" of that hook, i.e. the maximum time the fish could have been hooked.

Results and discussion

Seven 5-day PSATs were deployed on blue marlin off Bermuda (n=1) and Florida (n=6) during 2000, and two 30-day PSATs were deployed on blue marlin off North Carolina and Virginia during the summer of 2001 (Tables 1 and 2). Tags were attached onboard four vessels during six trips, ranging from one to eleven fishing days each. The captains all later indicated that the PSAT tagging procedures had minimal interference with normal longlining operations.

Although the captains attempted to target blue marlin by fishing in different areas and with slightly different gear than usual for swordfish trips, the catch rates for this species were not notably different from the catch rates in NMFS data; the catch rate for the trips in 2000 was slightly above average for both season and location, whereas the catch rate in 2001 was below the norm. Of the four trips in 2000, the average CPUE for blue marlin was approximately 0.08 per 100 hooks (7 blue marlin/8650 estimated total hooks), which is comparable to the reported blue marlin CPUE of 0.05 per 100 hooks for the NMFS southeast statistical region for the third quarter of 1998 (Cramer, 2000). For all billfish, excluding swordfish, the CPUE was 0.15 per 100 hooks (12 billfish/8650 estimated total hooks). This value is also comparable to the reported billfish CPUE of 0.12 per 100 hooks for the NMFS southeast statistical region for the third quarter of 1998 (Cramer, 2000). For the three trips in 2001, the blue marlin and billfish CPUEs were lower: 0.04 blue marlin per 100 hooks (3 blue marlin/7780 estimated total hooks) and 0.12 billfish per 100 hooks (9 billfish/7,780 estimated total hooks). These similar catch rates, even when targeting billfish, could be the result of decreased abundance, an inability of the gear to effectively target billfish, or unfavorable water conditions in the study areas.

Of the ten blue marlin caught on the trips, nine were alive and in relatively good physical condition. Based on

Table 1

Summary of pop-up satellite archival tag information for blue marlin (*Makaira nigricans*) released from pelagic longline gear in the western North Atlantic Ocean. Soak time is the maximum time that the blue marlin could have been hooked at that position on the longline. See text for a description of ACESS scores. .

Tag type	Tag number	Soak time (h)	Estimated weight (lb)	ACESS Score	Did tag report?
PTT-100	5D-1	11	200	10	yes
PTT-100	5D-2	12	325	10	yes
PTT-100	5D-3	13	250	10	no
PTT-100	5D-4	14	180	8	yes
PTT-100	5D-5	16	150	9	yes
PTT-100	5D-6	19	275	8	no
PTT-100	5D-7	9	120	10	yes
PAT	30D-1	6	400	10	yes
PAT	30D-2	35	350	9	yes

Table 2

Net movement of blue marlin released from pelagic longline gear in the western North Atlantic Ocean and equipped with pop-up satellite archival tags. Compass direction indicates the bearing from point of release to point of first transmission. Compass direction and straight-line distances between release and first transmission (net movement) were calculated with PROGRAM INVERSE (version 2.0, National Geological Survey, modified by M. Ortiz, NMFS Southeast Fisheries Science Center, Miami, FL). Distances are given in nautical miles (nmi), and kilometers (km). Note that the 30-day tags (30D-1 and 30D-2) did not have inclometers.

Tag number	Location of release	Location of first transmission	Compass direction	Net movement nmi (km)	Net movement per day (km)	Percentage of time less than 30 degrees above horizontal
5D-1	64.99°W, 31.99°N	64.10°W, 30.35°N	155°	107.8 (199.7)	21.2 (39.3)	46.77
5D-2	79.16°W, 28.64°N	79.48°W, 30.81°N	353°	130.8 (242.2)	25.7 (47.6)	47.74
5D-4	79.48°W, 28.59°N	78.37°W, 29.45°N	48°	77.0 (142.6)	15.1 (28.0)	46.77
5D-5	79.41°W, 28.58°N	77.48°W, 28.91°N	79°	103.7 (192.0)	20.4 (37.8)	47.72
5D-7	79.54°W, 28.69°N	78.09°W, 29.77°N	49°	100.0 (185.2)	19.7 (36.4)	47.29
30D-1	74.62°W, 36.79°N	62.10°W, 35.96°N	91°	608.3 (1,126.4)	19.6 (36.3)	—
30D-2	74.61°W, 34.67°N	50.08°W, 40.30°N	67°	1,214.7 (2,249.4)	39.2 (72.6)	—

a 10-point maximum, the ACESS score of the tagged blue marlin ranged from 8 to 10 (Table 1). Of the fish that received a score of less than 10, the primary reason was a loss of color, and minor body musculature lacerations. All blue marlin were hooked in the jaw, whether caught on a "J" hook (n=9) or a circle hook (n=1).

Soak time, the maximum period that the hooked fish could have been on the hook, did not appear to have an effect on either the reporting of the PSAT tags or the ACESS-scored physical condition of the blue marlin (Table 1). The two tags that did not report (5D-3 and 5D-6) were attached to fish with calculated soak times of 13 and 19 hours, respectively, both well under the maximum soak time of 35 hours. The one particularly long soak time (tag 30D-2) resulted from a parting of the mainline during an offshore storm and a subsequent two-day haulback. Boggs (1992) noted that substantial numbers of striped marlin were caught while gear was rising during haulback. Assuming similar behavior among other istiophorid species, this observation may explain the good to excellent condition noted for the blue marlin in our study even after extended soak times. Developing hook-timer technology may allow further description of the relationship, if any, between soak time and the actual length of time that a fish is hooked on the gear.

PSAT performance

The two PSAT models used for our study reflect the rapidly developing technology in this field. The difference in types and amounts of data recorded presented an apparent trade-off between the parameters measured (the resolu-

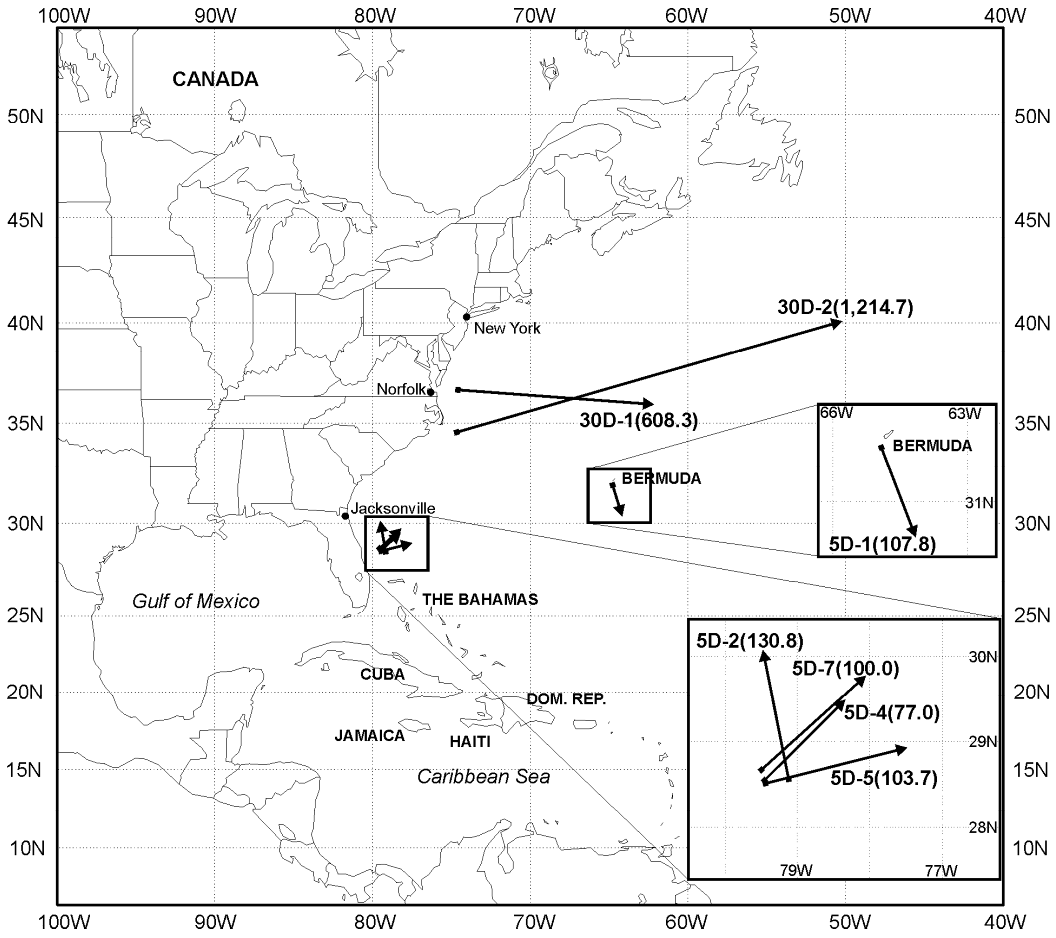

Figure 1

Map showing points of release (squares) and points of pop-up (arrow tips at end of straight lines) for seven of nine blue marlin released from pelagic longline gear in the western North Atlantic Ocean and equipped with pop-up satellite archival tags in 2000 and 2001. The tag identifier for each fish and straight-line distance in nautical miles between point of release and location where tag transmitted data to the Argos satellite are provided in parentheses.

tion of the data), and the probability of recovering (i.e. receiving) all the data recorded, as well as cost. The older, less-expensive 5-day tags stored far fewer data points but transmitted all of them. In contrast, the newer 30-day tags captured far more detailed data, yet only transmitted a fraction of them because of technological constraints, such as a short battery life, file corruption, and occasional problems with satellite uplink. Less than half of the 744 possible hourly histograms were recovered after final processing (46.5% for 30D-1 and 47.6% for 30D-2). However, of the reported histograms that were not corrupted, there was fairly consistent reporting across hours of the day, with an average of 14.75 records (range: 6–23) per hour of day for 30D-1 and 14.42 (range: 8–21) for 30D-2.

The small data storage capacity of the 5-day tag provided information regarding the thermal histories of blue marlin. However, the frequency of temperature recording, and subsequent averaging, limited the utility of the temperature data alone to infer survival. In contrast, the 30-day tags provided higher resolution data on temperature and depth, despite some significant gaps in the time series. In comparing the two tag models used in this study, the less expensive 5-day tags may be sufficient for the specific purpose of evaluating survival, although the greater detail provided by the 30-day tags may be desirable for additional behavioral analyses. Several models of archival satellite tags are currently available—all with differing data collection and storage capabilities. The high costs of tagging-related research, both for equipment and personnel time, therefore require choosing the tag model that is best matched to data needs to answer the specific scientific question of a study.

Net movement

All blue marlin tagged in this study undertook significant movements (Table 2, Fig. 1). The blue marlin released off Bermuda moved away from the islands 199.7 km (107.8 nmi) in a southeast direction over five days. Graves et al. (2002) noted similar movements away from the tagging locations for blue marlin released from the recreational fishery off Bermuda. The four blue marlin tagged off Florida during 2000 moved northeast to east in direction, which is inconsistent with the generally northward flow of the Gulf Stream as it exits the Florida Straits. Both the direction and distance moved by these five fish are evidence of their survival; had these fish been dead and floating, the expected path of movement would have been northward at a velocity of 1.5–3 knots in the Gulf Stream. Of the two fish tagged in 2001, one (30D-1) moved 1126.4 km (608.3 nmi) northeast toward the central north Atlantic, and the other (30D-2) moved 2249.4 km (1214.7 nmi) north toward the Grand Banks.

According to the minimum straight-line distances, blue marlin in this study moved an average of 0.95 nmi/hour (22.9 nmi/day average; range: 15.1–39.2 nmi), which is slightly faster than the average speed of 0.73 nmi/hour (17.6 nmi/day average; range: 10.9–26.4 nmi) reported by Graves et al. (2002). The results of both PSAT studies are consistent with the swimming velocities of 1–2 nmi/hour reported in the acoustic tracking of Pacific blue marlin by Holland et al. (1990), but at the lower end of the range of directly measured swimming speeds of 0.29–4.37 nmi/hour for blue marlin with an acoustic tag reported by Block et al. (1992). However, both measurements from acoustic studies were of short duration deployments. As noted in Block et al. (1992), high initial movement rates would be consistent with actions likely taken by ram-ventilating fish under oxygen debt; slower average speeds over the duration of the deployment could result from the averaging of high initial speed with later slower movements upon the return to normal behavioral patterns.

Forward movement and inclinometer data

The inclinometer values for each of the seven reporting 5-day tags indicated that the PSAT was depressed below 30° above horizontal for an average of 47.25% (range: 46.77–47.74%) of the measurements. These values indicate continual forward movement through the end of the 5-day sampling period and are similar to the observations of Graves et al. (2002), who reported substantial forward movement for more than 40% of their inclinometer measurements. They are also consistent with the observed net displacements of the blue marlin in the present study. Inclinometer values following release for all PSATs indicated that the tags were floating in a vertical position.

Depth and temperature

The temperature data of the 5-day tags indicated numerous vertical movements into cooler water for each fish (Fig. 2, A–E). The maximum temperature recorded by each tag was equivalent to, or slightly greater than, the sea surface temperature (SST) recorded by available SeaWIFS satellite data for that area and date. The slightly higher temperature is possibly an artifact of the 5-day tag; its black coloration may have absorbed heat from direct sunlight while at the surface. Each fish demonstrated movement into slightly cooler waters immediately following release, a behavior also noted in acoustic tracking studies (e.g. Holland et al., 1990; Holts and Bedford, 1993), although it is likely that this movement to cooler waters was still within the upper strata of the water column.

Differences in vertical behavior were noted among individuals. The vast majority (98.6%) of values reported by the 5-day tag on the Bermuda-released fish fell within a range of 2°C (28.6°–30.6°C) (Fig. 2A). This range is smaller than those reported by Graves et al. (2002) for blue marlin in the same general area (range: 26–31°C) but of a much smaller sample size (n=1 vs. n=8 recovered tag datasets). The four blue marlin tagged with 5-day tags off Florida exhibited greater variation in thermal habitat, but their temperature values remained within a range of 6.5°C (Fig. 2, B–E). These four fish also displayed greater vertical movements during the morning hours, especially 5D-3 and 5D-7 (Fig. 2, B and E). For the four blue marlin tagged with 5-day PSATs off Florida in 2000, there was a significant difference between the average temperature during the night, day, and a composite dawn and dusk period (one-way ANOVA; P=0.0003, 2 df).

The 30-day PSATs provided much more detailed temperature information than the 5-day tags, as well as depth data, allowing for a higher resolution of blue marlin vertical movements over the course of a day. The two fish with the 30-day tags spent the vast majority of their total time within the upper five meters of the water column (65.4% for tag 30D-1 and 81.5% for 30D-2, Fig. 3). The higher temperatures recorded by tag 30D-1 are likely due to the warmer surface waters encountered by that fish as it moved toward the central Atlantic, whereas the blue marlin with tag 30D-2 moved northeast into cooler waters near the Grand Banks (Fig. 1). Examination of the temperature histograms generated the by tags for each hour-long period also indicates that these two fish spent all of the first two (30D-1) and six (30D-2) days following release at or near the surface (depth ≤5 m). Only after this initial period did the fish resume the repetitive deep diving behavior seen later during the deployments.

The two 30-day tags deployed in 2001 recorded a broader range of temperatures (30D-1: 29.6–17.8°C and 30D-2: 30.6–16.6°C) than the 5-day tags attached to the blue marlin in 2000. This apparent difference may relate to the measurement protocol of each type of tag. The 5-day tags recorded temperature once an hour and stored the average of two hourly values. In contrast, the 30-day tags recorded temperature values every minute and stored them in the form of an hourly histogram. Inspection of the 30-day tag data revealed that excursions into cooler water were typically of short duration. It is therefore likely that such an excursion could have been missed with a once-an-hour temperature measurement by the 5-day tag. Alternatively, if a lower temperature were encountered at one measurement, it would probably be increased by being averaged with another (likely warmer) measurement from the previous or next hour before being archived. It can be shown mathematically that if the two observations in each pair are independent (which would occur if they are sufficiently separated in time), then the effect of averaging them would be to reduce the variance by one-half. However, cases can be constructed where the observations in each pair would not

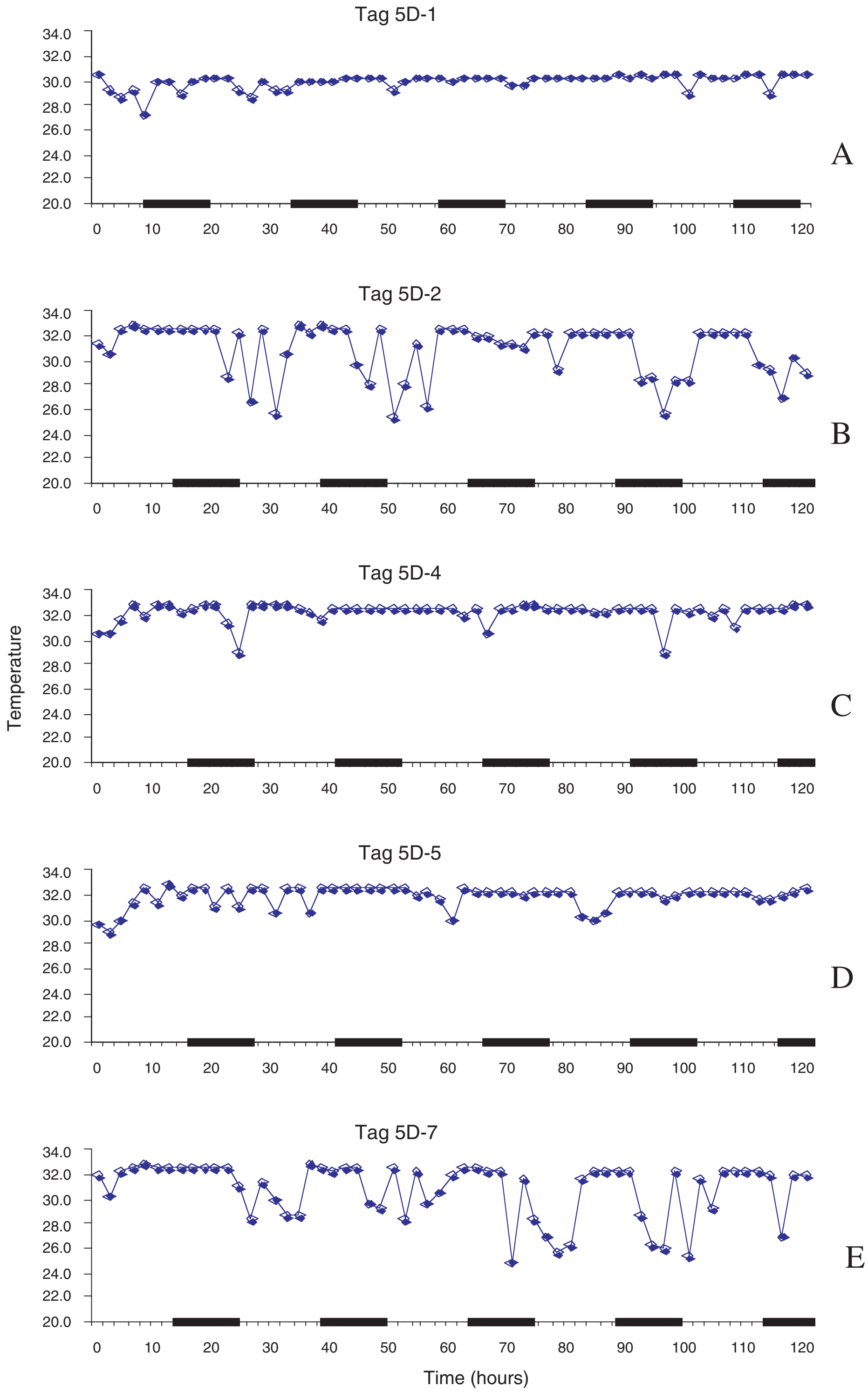

Figure 2

Temperature records for blue marlin released from pelagic longline gear in the western North Atlantic Ocean and equipped with PTT-100 (5-day) pop-up satellite archival tags. Temperature readings were taken once an hour and the average value of two consecutive hours was stored. Temperatures are in degrees centigrade, and the black bars indicate approximate hours of darkness.

be independent. It is therefore not possible to accurately describe the effects (i.e. to reconstruct the actual data or data ranges) of the averaging process of the 5-day tags. Although we feel that any direct comparison of inferred 5-day tag data with the observed data from the 30-day tags would be inappropriate because of the inability to describe this averaging effect, we note that the reported 5-day tag data are not inconsistent with those data from the 30-day tags.

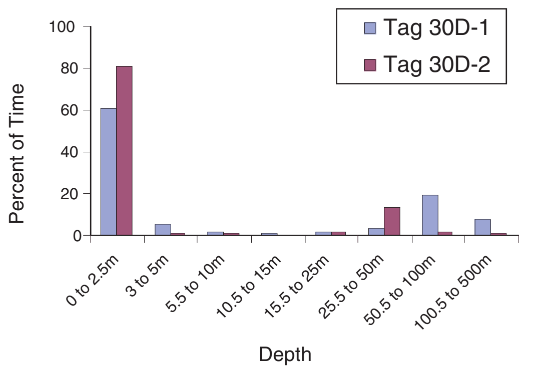

Figure 3

Percentage of total time at depth for blue marlin released from pelagic longline gear in the western North Atlantic Ocean and equipped with PAT (30 day) pop-up satellite archival tags.

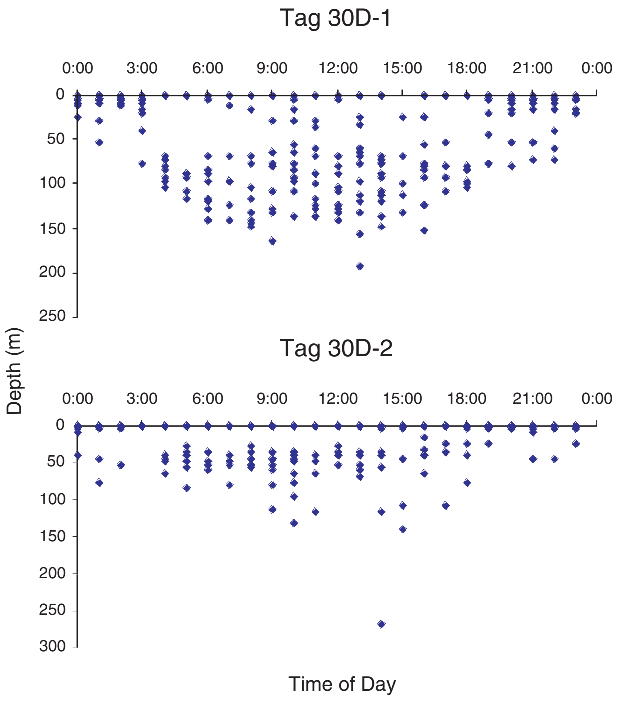

Figure 4

Maximum depths as a function of time of day for blue marlin released from pelagic longline gear in the western North Atlantic Ocean and equipped with PAT (30-day) pop-up satellite archival tags. Both individuals demonstrated a tendency to have greater maximum depths during daylight hours.

The 30-day tags provided considerable information on blue marlin movements at depth. Each hour-long histogram included both the maximum and minimum depths for the hour interval, as well as the percentage of time spent within each predetermined depth bin. For example, during the hour between 10:00 and 11:00 a.m. on 25 July, 30D-1 reported a maximum depth of 28 m and a minimum depth of 0 m, During this hour the fish spent 42 minutes between 0 and 2.5 m, only 72 seconds between 3 and 15 m, and almost 17 minutes between 15.5 and 28 m.

Examination of the maximum and minimum depth values by hour suggests a relationship between movement to depth and daylight hours (Fig. 4). Both blue marlin with 30-day tags made deeper dives during the day than at night. This pattern is similar to diurnal vertical migrations observed in bigeye tuna (*Thunnus obesus*) (Holland et al., 1990; Dagorn et al., 2000), and swordfish (Sedberry and Loefer, 2001) and may relate to feeding within the deep scattering layer.

Billfish survival

Seven of the nine deployed tags successfully reported data. Three independent lines of data transmitted by these tags suggest that seven of the blue marlin carrying these tags and released from pelagic longline gear survived for periods of five or thirty days. First, changes in temperature (5-day tags) or temperature and depth (30-day tags) were consistent with vertical excursions within the water column. Secondly, the direction and magnitude of net displacement cannot be explained by local current patterns and thus imply active movement. Finally, the inclinometer readings (5-day tags only) are consistent with sufficient forward propulsion to depress tags below 30° above horizontal for almost one-half of the measurement periods.

The thermal histories of three fish tagged with 5-day tags (5D-1 off Bermuda and 5D-4 and 5D-5 off Florida) showed little variation (Fig. 2, A, C, and D). Because of the infrequent sampling of temperature by these tags (once an hour, and two hourly values were averaged), it is possible that short-duration dives to cooler waters were not sampled, or that detailed information was lost in the averaging of the two hourly measurements. Alternatively, the thermal histories for these tags could be interpreted as those of fish that died and remained floating at the surface. However, given the preference of individuals for shallow depths recorded by the 30-day tags, even the minimal variations in temperature observed by the 5-day tags may be consistent with movement to depths and postrelease survival. Additionally, the net displacements cannot be attributed solely to local currents (Fig. 1), and inclinometer values indicate continued forward movement throughout the five-day period. We maintain, therefore, that these fish were alive for the whole five-day post-release period.

The reason that two tags did not report data could have been result of mortality (the blue marlin died and sank to a depth at which the tag was crushed or lost positive buoyancy) or of other factors, such as tag malfunction or mechanical damage to the tag. Neither tag contained prerelease software or an emergency release device. There did not appear to be a relationship between the weight of the fish and a nonreporting tag. Both fish with nonreporting tags were hooked in the jaw with "J" hooks. The blue marlin with tag 5D-3 was in excellent condition and actively swam away from the vessel, whereas the fish that received tag 5D-6 was in good condition and actively swam away from the vessel, albeit more slowly than several of the others. It is worth noting that this fish also had an orange streamer tag attached to it from a previous capture, but it was not possible to retrieve this tag without compromising the release protocol.

The results of the present study can be used to generate rough estimates of postrelease survival rate for blue marlin released from the western North Atlantic pelagic longline fishery. This project observed that seven of nine deployed PSATs reported data as programmed (if the two nonreporting tags were indeed mortalities); this results in a 77.8% postrelease survival rate. Combining postrelease mortalities with estimates of mortality at the time of haulback, the compounded mortality for blue marlin conservatively ranges from 65.4% (Jackson and Farber, 1998) to 53.5% (Cramer, 1998). However, the relatively small number of tags deployed in this study clearly limits the general applicability of the these results, as did the prior limitation that only live fish greater than 100 pounds, without clearly mortal wounds, would be tagged. Fortunately, all of the fish encountered alive (one was dead on haulback) met these two requirements. The 77.8% estimate of postrelease survival is nevertheless comparable with the 89% survival rate (8 of 9 reporting PSAT tags) reported by Graves et al. (2002) for blue marlin caught in the recreational fishery off Bermuda—a fishery in which many blue marlin are resuscitated prior to release.

The sample size required for an Atlantic-wide estimate of postrelease mortality would be large given the need to account for different gear configurations, as well as variables such as environmental conditions, season, and geographic area (Goodyear, 2002). Such a project would be extremely expensive with current technology. However, evolving PSAT technology presents the opportunity for additional work describing the interactions between pelagic longline gear and catch species, such as the billfishes. New high-resolution PSATs provide fine-scale data on habitat preferences and behavior, allowing the eventual refinement of models that standardize historical catch-per-unit-of-effort data for pelagic longline gear (e.g. Hinton and Nakano, 1996; Hinton, 2001). Such standardization efforts, if correctly applied, may permit more accurate blue marlin stock assessments (Venizelos et al., 2001).

This study demonstrates that PSAT technology is well suited to estimate postrelease survival rates for blue marlin from the pelagic longline fishery, with minimal interference to normal commercial fishing operations. The relatively high rate of survival of blue marlin inferred from these data for five and thirty days following release from pelagic longline gear demonstrates that management measures requiring live release, such as those recently adopted by ICCAT, can significantly reduce fishing mortality on Atlantic blue marlin.

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Literature cited

Apgar, V.
1953. A proposal for a new method of evaluation of the newborn infant. Curr. Res. Anesth. Analg. July–August: 260–265.

Arnold, G., and H. Dewar.
2001. Electronic tags in marine fisheries research: a 30-year perspective. *In* Electronic tagging and tracking in marine fisheries (J. R. Sibert and J. L. Nielsen, eds.), p. 7–34. Kluwer Academic Publishers, Dordrecht, Netherlands.

Bayley, R. E., and E. D. Prince.
1994. A review of tag release and recapture files for *Istiophoridae* from the Southeast Fisheries Science Center's Cooperative Gamefish Tagging Program, 1954 to present. ICCAT (Int. Comm. Conserv. Atl. Tunas) Coll. Vol. Sci. Pap. 41:527–548.

Block, B. A., D. T. Booth, and F. G. Carey.
1998. Depth and temperature of the blue marlin, *Makaira nigricans*, observed by acoustic telemetry. Mar. Biol. 114: 175–183.

Block, B. A., H. Dewar, C. Farwell, and E. D. Prince.
1998. A new satellite technology for tracking the movements of Atlantic bluefin tuna. Proc. Natl. Acad. Sci. U. S. A. 95: 9384–9389.

Boggs, C. H.
1992. Depth, capture time, and hooked longevity of longline-caught pelagic fish: timing bites of fish with chips. Fish. Bull. 90:642–658.

Cramer, J.
1998. Pelagic longline billfish by-catch. ICCAT (Int. Comm. Conserv. Atl. Tunas) Coll. Vol. Sci. Pap. 47:143–154.
2000. Species reported caught in the U.S. commercial pelagic longline and gillnet fisheries from 1996 to 1998. NMFS Sustainable Fisheries Division SFD-99/00-78:1–33.

Dagorn, L., P. Bach, and E. Josse.
2000. Movement patterns of large bigeye tuna (*Thunnus*

obesus) in the open ocean, determined using ultrasonic telemetry. Mar. Biol. (Berlin) 136(2):361–371.

Goodyear, C. P.
2000. Biomass projections for Atlantic blue marlin: potential benefits of fishing mortality reductions. ICCAT (Int. Comm. Conserv. Atl. Tunas) Coll. Vol. Sci. Pap. 52: 1502–1506.
2002. Factors affecting robust estimates of the catch and release mortality using pop-up tag technology. *In* Symposium on catch and release in marine recreational fisheries (A. Studholme, E. D. Prince, and J. Lucy, eds.), p. 172–179. Spec. Pub. Am. Fish. Soc.

Graves, J. E., B. E. Luckhurst, and E. D. Prince.
2002. An evaluation of pop-up satellite tags for estimating post-release survival of blue marlin (*Makaira nigricans*). Fish. Bull. 100:134–142.

Hinton, M.G.
2001. Status of the blue marlin in the Pacific Ocean. Status of the tuna and billfish stocks in 1999. IATTC Stock Assess. Rep. 1:284–318.

Hinton, M.G., and H. Nakano.
1996. Standardizing catch and effort statistics using physiological, ecological, or behavioral constraints and environmental data, with an application to blue marlin (*Makaira nigricans*) catch and effort data from the Japanese longline fisheries in the Pacific. Inter.-Am. Trop. Tuna Comm. Bull. 21(4):171–200.

Holland, K., R. Brill, and R. K. C. Chang.
1990. Horizontal and vertical movements of Pacific blue marlin captured and released using sportfishing gear. Fish. Bull. 88:397–402.

Holts, D. B., and D. W. Bedford.
1993. Horizontal and vertical movements of the shortfin mako shark, *Isurus oxyrinchus*, in the southern California bight. Aust. J. Mar. Freshw. Res. 44(6):901–909.

ICCAT (International Commission for the Conservation of Atlantic Tunas).
1997. Report for the biennial period, 1996–97. Part I (1996), vol. 2, 204 p. ICCAT, Madrid, Spain.
2001. Report of the fourth ICCAT billfish workshop. ICCAT Coll. Vol. Sci. Pap. 53:1–22.

Jackson, T. L., and M. I. Farber.
1998. Summary of at-sea sampling of the western Atlantic Ocean, 1987–1995, by industrial longline vessels fishing out of the port of Cumaná, Venezuela: ICCAT enhanced research Program for billfish 1987–1995. ICCAT Coll. Vol. Sci. Pap. 47:203–228.

Jones, C. D., and E. D. Prince.
1998. The cooperative tagging center mark-recapture database for Istiophoridae (1954–1995) with an analysis of the west Atlantic ICCAT billfish tagging program. ICCAT Coll. Vol. Sci. Pap. 47:311–322.

Lee, D. W., and C. J. Brown.
1998. SEFSC pelagic observer program data summary for 1992–1996. NOAA Tech. Memo. NMFS-SEFSC-408:1–21.

Lutcavage, M. E., R. W. Brill, G. B. Skomal, B. C. Chase, and P. W. Howey.
1999. Results of pop-up satellite tagging of spawning size class fish in the Gulf of Maine: do North Atlantic bluefin tuna spawn in the mid-Atlantic? Can. J. Fish. Aquat. Sci. 56(2):173–177.

Ortiz, M., D. S. Rosenthal, A. Venizelos, M. I. Farber, and E. D. Prince.
1998. Cooperative Tagging Center annual newsletter: 1998. NOAA Tech. Memo. NMFS-SEFSC-423:1–23.

Pepperell, J. G., and T. L. O. Davis.
1999. Post-release behavior of black marlin *Makaira indica* caught and released using sportfishing gear off the Great Barrier Reef (Australia). Mar. Biol. 135:369–380.

Sedberry, G. R., and J. K. Loefer.
2001. Satellite telemetry tracking of swordfish, *Xiphias gladius*, off the eastern United States. Mar. Biol. 139: 355–360.

Venizelos, A., M. I. Farber, and D. D. Benetti.
2001. An evaluation of assumptions associated with blue marlin depth distribution towards the possible incorporation to the standardization of catch and effort statistics for use in stock assessment. ICCAT Coll. Vol. Sci. Pap. 53: 258–262.

Zar, J. H.
1999. Biostatistical analysis, 4th ed., 663 p. Prentice-Hall, Inc., Upper Saddle River, NJ.