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Archival tagging of a basking shark, *Cetorhinus maximus*, in the western North Atlantic

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A 6.1-m long female basking shark (*Cetorhinus maximus*) was tagged 73 km east of Nantucket Island, Massachusetts on 27 September 2001 with a pop-up archival transmitting tag. The tag detached prematurely on 6 December 2001 in an area approximately 800 km southwest of the tag site off the coast of North Carolina. The basking shark was vertically active for the 71-day tracking period, moving through depths and temperatures ranging from the surface to 320 m and 5.8 to 21.0°C, respectively. The shark displayed temporal variation in its residence depth and exhibited a marked temperature preference, with 72% of the temperature observations between 15.0 and 17.5°C. This track provides evidence that the basking shark associates with the continental shelf and shelf edge off the southeastern United States during autumn. Moreover, it corroborates previous studies indicating that the basking shark remains active and does not hibernate during autumn.

INTRODUCTION

The basking shark, *Cetorhinus maximus* (Gunnerus), is the world's second largest fish, but little is known of its life history and ecology. The species is broadly distributed in northern and southern temperate waters of the Atlantic and Pacific oceans, and found from brackish coastal lagoons and shallow coastal waters to the open ocean (Francis & Duffy, 2002). In spring and summer, the basking shark moves inshore to feed on planktonic crustaceans, but little is known of its autumn and winter habitats in most of its range (Francis & Duffy, 2002). The paucity of winter observations and the discovery of several sharks lacking gillrakers prompted Parker & Boeseman (1954) to propose that basking sharks hibernate during winter because zooplankton densities are too low to make feeding energetically profitable. This hibernation hypothesis has persisted for decades, though there are now theoretical considerations (Sims, 1999) and bycatch records (Francis & Duffy, 2002) to the contrary. Recently, Sims et al. (2003) investigated the seasonal movements and behaviour of the basking shark in the eastern North Atlantic using pop-up archival transmitting (PAT) tags. They found that basking sharks remain vertically and horizontally active in late autumn and early winter. Moreover, they suggested that basking sharks exploit continental shelf and slope regions associated with mesopelagic and epipelagic zooplankton habitats.

In the western North Atlantic, the basking shark concentrates in spring and summer in areas of high productivity and along thermal fronts on the continental shelf from southern New England to Newfoundland (Templeman, 1963; Owen, 1984). Although North Atlantic stock structure has yet to be defined for this species, tagging data suggest separate eastern and western stocks (Kohler et al., 1998). The autumn and winter habitat of *C. maximus* in the western North Atlantic remains largely unknown despite limited evidence that the species may move into waters off the south-eastern United States (Schwartz & Burgess, 1975; Springer & Gilbert, 1976). Moreover, the seasonal movements, vertical behaviour, and possible habitat preferences of basking sharks relative to oceanographic features remain a mystery during that time of year.

MATERIALS AND METHODS

On 27 September 2001 we tagged a ~6.1-m total length female basking shark 73 km east of Nantucket Island, Massachusetts (41.29°N, 69.08°W) using a PAT tag (Wildlife Computers, Redmond, WA, USA). The tag was programmed to record swimming depth (minimum resolution: 0.5 m), water temperature (minimum resolution: 0.05°C), and light level (measured as irradiance at 550 nm wavelength) every minute. These data were compiled and stored by the tag as three types of summary data over a set interval of three hours. First, depth and temperature measurements were aggregated into 12 pre-specified depth bins (<10 m, 10 to 25 m, 25 to 50 m, 50 to 75 m, 75 to 100 m, 100 to 150 m, 150 to 200 m, 200 to 300 m, 300 to 500 m, 500 to 750 m, 750 to 1000 m, >1000 m) and 12 pre-specified temperature bins (<5.0°C, 5.0 to 7.5°C, 7.5 to 10°C, 10.0 to 12.5°C, 12.5 to 15°C, 15.0 to 17.5°C, 17.5 to 20.0°C, 20.0 to 22.5°C, 22.5 to 25.0°C, 25.0 to 27.5°C, 27.5 to 30.0°C, 30.0 to 60.0°C), respectively. Second, the tag compiled a temperature–depth profile of the water column inhabited by the shark during each three hour interval. This comprised minimum and maximum water temperatures at eight equally spaced depths, which ranged from the shallowest to the deepest swimming depths. Finally, the tag processed the light level data to correct for depth and then estimated times of dawn, dusk, and midnight or midday.

The tagged shark was part of an aggregation of 10 to 12 basking sharks. The sea surface temperature in the tagging area was 16.7°C and none of the sharks in the aggregation was observed feeding. The PAT tag was applied by a diver along the dorsal midline just posterior to the first dorsal fin with an intramuscular stainless steel dart. The dart was placed approximately 7 to 10 cm into the dorsal musculature, with the tag trailing on a 20 cm length of heavy monofilament nylon line with chafing protection. During the tagging process, the entire group of sharks descended.

The PAT tag was programmed to release from the shark and to transmit data summaries on 14 February 2002, a time when the distribution of the basking shark in the western North Atlantic is unknown. Moreover, we chose a relatively short tag deployment to assess tag attachment. To construct the track of the shark, estimates of its longitude and latitude positioning were computed from light level messages with an algorithm developed by the PAT manufacturer (PAT Decoder, Wildlife Computers). Assuming an accuracy of ±0.9° longitude and ±1.2° latitude (Welch & Eveson, 1999), position estimates were

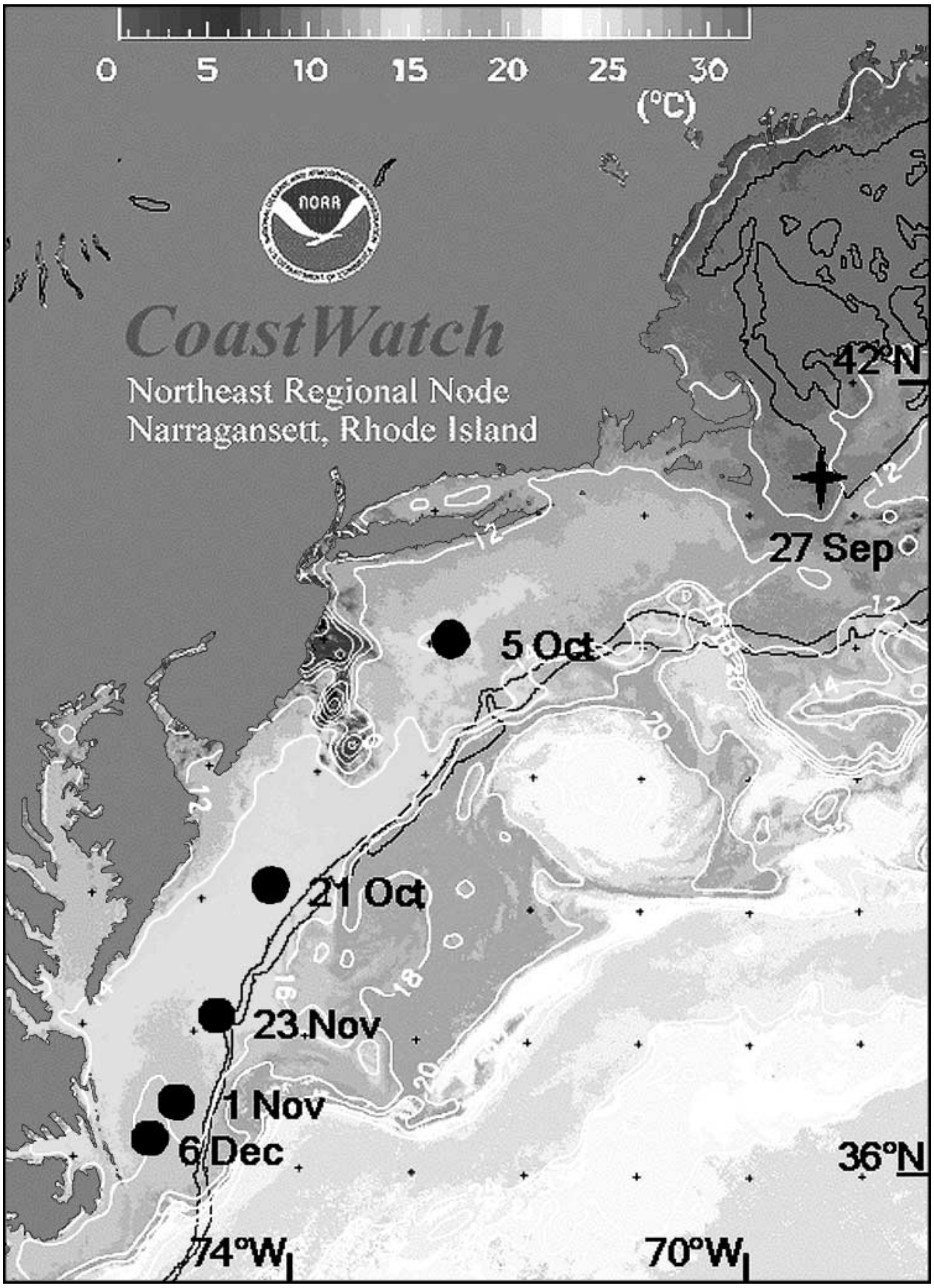

Figure 1. Estimated track of a 6.1 m basking shark tagged 27 September 2001 plotted on an AVHRR SST image of 6 December 2002, the date of detachment (several estimated positions were not plotted due to point overlap); lines delineate 100 m and 200 m bathymetry curves (black) and isotherms (white). Star indicates tagging location.

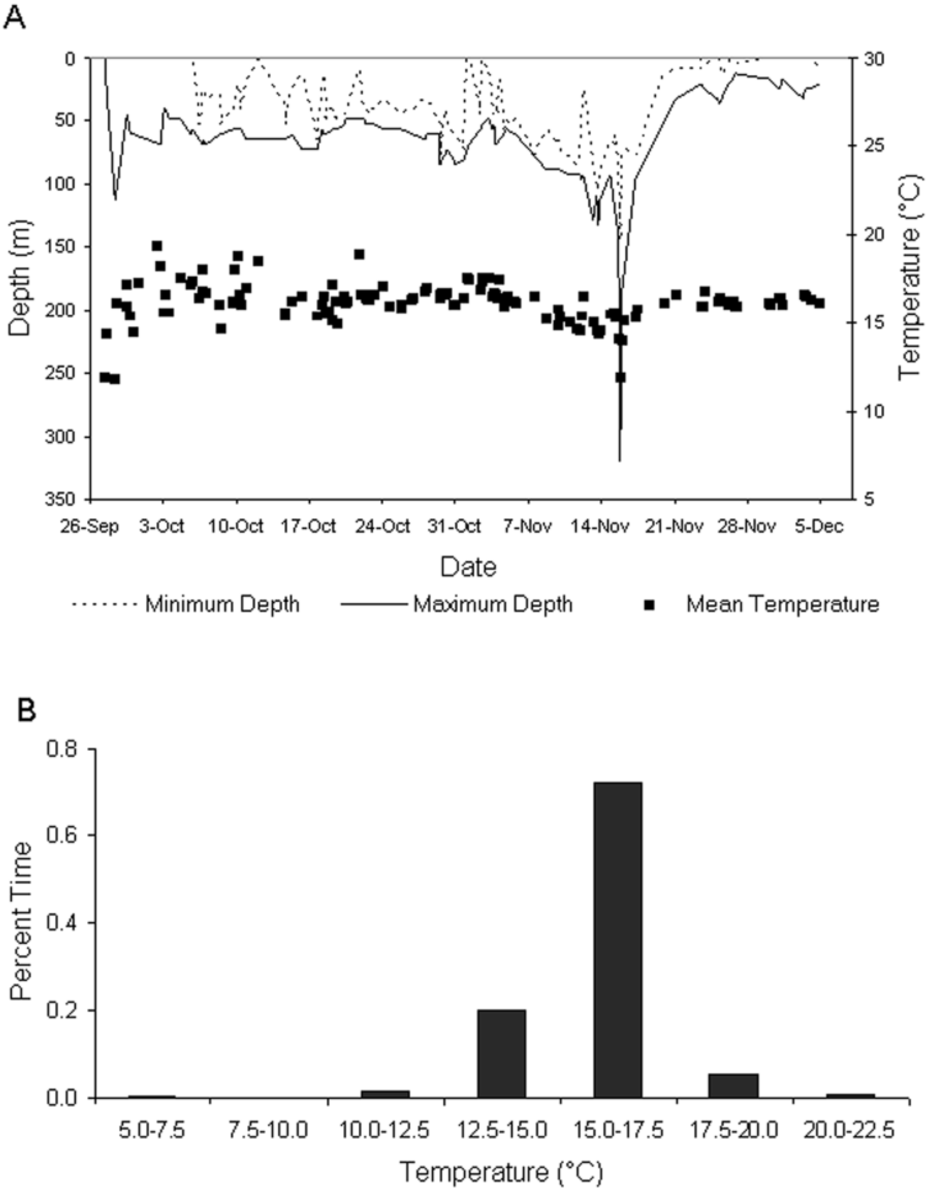

Figure 2. Swimming depth and water temperature data from a PAT-tagged basking shark tracked in the western North Atlantic: (A) minimum and maximum swimming depths and average water temperatures collected every three hours; (B) percentage time-at-temperature histogram of measurements collected over the duration of the track.

refined using Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) images and bathymetry data coupled with depth and temperature profile data collected by the tag.

RESULTS

The tag began transmitting data on 14 February 2002 from an area in the central North Atlantic (36.48°N, 45.81°W) about 2100 km southeast of the tag site. However, depth and temperature data collected by the tag indicated that the tag detached prematurely between 0900 and 1200 on 6 December 2001. The cause of the early detachment remains unknown, but in December 2002 we received notification from the tag manufacturer of a potential problem with the stainless steel release pin. The eastward movement of the floating tag after its release closely followed the flow of the Gulf Stream.

The light data collected by the tag allowed the estimation of 40 positions along the track of the basking shark using the algorithm developed by the PAT manufacturer. However, in consultation with the tag manufacturer, many of these were discarded due to light degradation associated with the depth of the animal and time of year, or they could not be corroborated with satellite imagery and behavioural data. This filtering process resulted in 15 position estimates that were used to construct the track of the shark. These estimates indicated that the tag released from the shark in an area approximately 800 km southwest of the tag site, off the Outer Banks of North Carolina (near 36.00°N, 75.30°W) (Figure 1). The basking shark moved out of southern New England waters shortly after tagging, yet remained on the continental shelf for the duration of the track and, at times, was associated with the shelf edge (Figure 1). When position estimates were superimposed on satellite SST images, the southern

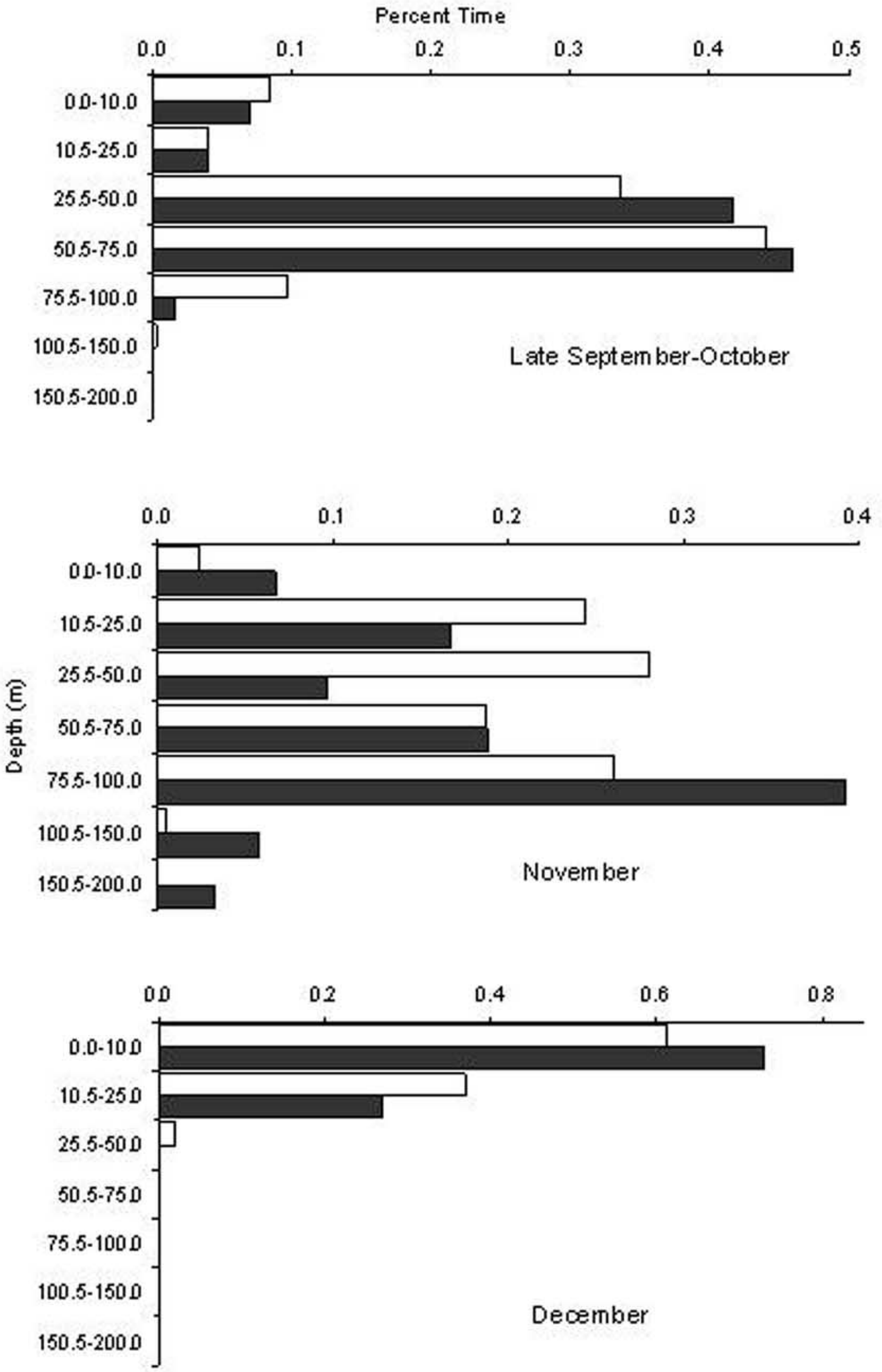

Figure 3. Monthly depth histograms from PAT-tagged basking shark during the day (white) and night (black).

movements of the animal appeared to coincide with the seasonal cooling of more northerly continental shelf waters. By 5 October, the shark had moved southwest from the Gulf of Maine to shelf waters in the mid-Atlantic Bight east of New Jersey (Figure 1). The shark continued to move southwest as shelf waters cooled and on 21 October the shark was on the outer shelf southeast of Delaware Bay. By 1 November, the shark was northeast of the Outer Banks of North Carolina. It remained in that general region for the next month, moving slightly northeast in late November, and back to the Outer Banks by 6 December.

The basking shark was vertically active for the entire tracking period, moving though depths ranging from the surface to 320 m (Figure 2). Although the shark encountered water in the temperature range of 5.8 to 21.0°C, 72% of the observations were within the range 15 to 17.5°C (Figure 2). Over the 71-day track, the shark displayed some temporal variation in residence depth (Figures 2,3). In late September and October, tracking data indicated that the shark resided within a depth range of 25 to 75 m for 83% of the time and there was little difference between day and night observations (Figure 3). During this period, the shark made occasional forays to the surface. In November, the vertical behaviour of the shark was more variable and deeper, particularly during the night, with fewer surface forays. Although most of the track was shallower than 100 m, the shark made a single dive to 320 m on 15 November and was likely on the edge of the shelf at this time. For the balance of the track, the shark displayed shallow behaviour and remained in the top 25 m for 99% of the first week in December (Figures 2,3).

DISCUSSION

The track reported herein indicates that the tagged *Cetorhinus maximus* moved south on or near the edge of the continental shelf in autumn from its northern summer feeding areas in the western North Atlantic. This southerly movement appears to coincide with the seasonal cooling of more northerly continental shelf waters. SST data collected in the Gulf of Maine by the National Data Buoy Center showed a rapid cooling coincident with the departure of the shark from these waters in early October. The mean daily water temperature dropped from 15.8°C on 26 September to 12.7°C on 30 September 2001, which is below the thermal preference exhibited by the shark (Figure 2). Using aerial survey data, Owen (1984) investigated the seasonal movements of the basking shark in the Gulf of Maine and southern New England. He found that the temporal and spatial distribution of the basking shark were largely functions of seasonal water stratification, temperature, and prey abundance. Sharks were sighted in a SST range of 11 to 24°C, but peak densities occurred in waters of 22 to 24°C; well above the thermal range of the shark we report here. All of Owen's (1984) sightings in the mid-Atlantic Bight occurred on the continental shelf, but he reported only three sightings in autumn and found that basking shark abundance decreased before zooplankton densities declined. Many of the 156 basking sharks reported in Kohler et al. (1998) were tagged on or closely associated with the edge of the continental shelf from southern New England to Chesapeake Bay. Similarly, five PAT-tagged basking sharks in the eastern North Atlantic exhibited broad movements confined to the continental shelf and remained within discrete areas of high productivity, which occur seasonally along large-scale frontal features (Sims et al., 2003).

The general region off the Outer Banks of North Carolina may represent the over-wintering habitat of the basking shark in the western North Atlantic. This is a dynamic oceanographic region where the northward flowing Gulf Stream closely approaches the coast of North Carolina. Steep thermal gradients and frontal zones are common in the area and our data indicated that the tagged basking shark was associated with these potential areas of high productivity (Figure 1). The shark remained in this area from early November until the termination of the study in early December, presumably foraging in areas of high productivity. This is further substantiated by Schwartz & Burgess (1975), who reported that the species occurs off North Carolina from December through March, with seasonal movements north as water warms above 10°C.

The seasonal movements of this basking shark may have been mediated by temperature as it affects foraging opportunities. Plankton concentration data collected by the National Marine Fisheries Service (NMFS) from 30 October to 16 November 2001 indicated that the concentration of copepods on the continental shelf from Cape Hatteras to the Gulf of Maine remained well above the minimum threshold foraging density ($\sim$400 copepods m^{-3}) estimated by Sims (1999) for the basking shark (J. Prezioso, Ecosystems Monitoring Group, NMFS, 28 Tarzwell Drive, Narragansett, RI, personal communication). However, feeding opportunities rapidly diminished in the Gulf of Maine during the subsequent winter months. Copepod abundance data collected at 47 stations in this area from 23 to 30 January 2002 indicated concentrations below this threshold at all but two stations. Moreover, water temperature data collected during the survey ranged from 4.0 to 9.3°C, well below the temperature range exhibited by the shark. The seasonal decline of copepod abundance exhibited in the western North Atlantic sharply contrasts the eastern North Atlantic, where plankton densities remain above basking shark feeding threshold levels in the winter (Sims et al., 2003).

The winter habitat of the basking shark has been the subject of long debate over the last century and it has been hypothesized that basking sharks hibernate in deep water off the continental shelf (Parker & Boeseman, 1954). Based on catch records, Francis & Duffy (2002) provided evidence that basking sharks off New Zealand do not hibernate, but overwinter in deep water on the continental slope. Sims et al. (2003) concluded that the habitat of the basking shark in the eastern North Atlantic remained similar in the summer, autumn, and early winter. This finding is corroborated by the basking shark in our report, which remained on the continental shelf and was vertically active throughout the tracking period. Sims et al. (2003) found that three PAT-tagged basking sharks remained on the shelf during December and early January. Two of these sharks were tagged and recovered in the English Channel, the third shark exhibited southern movements similar to those demonstrated in the current study. That shark left the tagging site in the Clyde Sea in mid-September and moved 555 km south over the next month to continental shelf and shelf-edge areas off southwest England where it remained until the tag jettisoned in early January. Similarly, our basking shark exhibited movements in October from northern summer feeding grounds off New England to potential winter habitat in the mid-Atlantic Bight. The basking sharks tagged by Sims et al. (2003) in the eastern North Atlantic exhibited a broader vertical range (0–1000 m) than the shark in the current study, but this is largely due to the shallower depths of the area inhabited by the latter. In both studies, the basking sharks appeared to exploit the entire water column, which may be attributed to prey-searching behaviour (Sims et al., 2003).

This study provides a first glimpse into the vertical and horizontal movements and temperature preferences of the basking shark in the western North Atlantic, but additional PAT tagging of basking sharks is needed to further elucidate the seasonal movements and habitat range of this species in this region.

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