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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?

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Abstract: Twenty giant bluefin tuna were captured in September and October 1997 and tagged and released with pop-up satellite tags programmed to jettison from March through July, 1998. Seventeen tags successfully released from the fish (12 during the known May–July spawning period), all of which were located north of 33°N latitude, in a region of the mid-Atlantic bounded by Bermuda and the Azores. Our results argue for reconsideration of current assumptions about North Atlantic bluefin tuna migration patterns, mixing rates, spawning areas, and stock structure and highlight the need for additional studies.

Résumé : En septembre et octobre 1997, on a capturé vingt thons rouges géants, que l'on a relâchés après leur avoir fixé des étiquettes détachables pistées par satellite qui devaient se libérer de mars à juillet 1998. Dix-sept étiquettes ont bien été libérées (dont 12 pendant la période de fraye connue de mai à juillet), toutes au nord de 33N, dans une région du centre de l'Atlantique délimitée par les Bermudes et les Açores. Nos résultats portent à reconsidérer les hypothèses actuelles sur les régimes migratoires du thon rouge dans l'Atlantique Nord, le taux de mélange, les zones de fraye, et la structure du stock, et mettent en évidence la nécessité de nouvelles études.

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The North Atlantic bluefin tuna, *Thunnus thynnus*, is a highly migratory species present in large schooling assemblages in New England and Canadian waters from June through November. Bluefin tuna populations have been reduced by intense fishing pressure worldwide, and U.S. and Canadian fisheries are subject to strict quotas. Since 1982, North Atlantic bluefin tuna have been managed under the International Commission for the Conservation of Atlantic Tunas (ICCAT) as separate east and west Atlantic stocks with substantially different fishing control levels. Mixing rates are estimated at 2% to 7% yearly (Restrepo 1996) but are ignored in stock assessments. However, the status and stock structure of the population remain controversial, and current models of long-term migrations include assumptions on trans-Atlantic movements and spawning site fidelity that have not been extensively tested.

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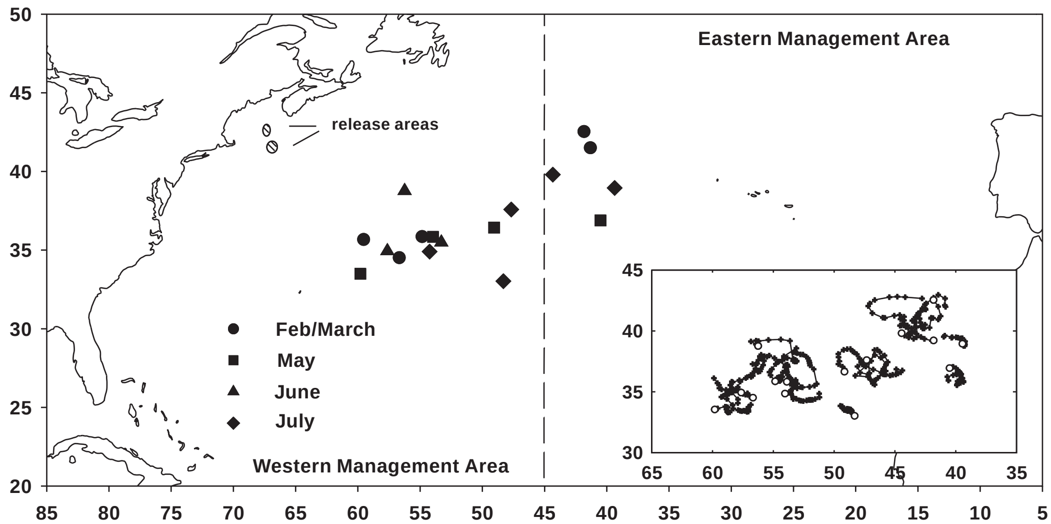
The majority of bluefin tuna caught in New England are in size classes representative of sexually mature fish (Mather et al. 1995). After foraging in the Gulf of Maine and adjacent continental shelf, bluefin tuna are presumed to disperse to the south and east and eventually to return and spawn in the Gulf of Mexico by April–June (Richards 1976; Rivas 1978; McGowan and Richards 1989). However, during presumed spawning periods, adult bluefin tagged in New England have been recaptured throughout the Atlantic and Mediterranean Sea (Mather et al. 1995), and Japanese longline records also show their continuous distribution across the Atlantic (Shingu and Hisada 1977).

Utilizing a new technology, we undertook a bluefin tagging experiment to identify long-range migration patterns of the New England assemblage. We employed the pop-up satellite tag (model PTT 100 PU1) designed and built by Telemetry 2000, Inc. (Columbia, MD), that was recently proven in short-term deployments (Block et al. 1998). Tags consist of a streamlined carbon–epoxy pressure housing plus antenna, a corrosive release mechanism, and a flotation collar that allows the antenna to float upright when the tag jettisons from the fish. A microprocessor records up to 61 average daily water temperatures (sampled hourly). The re-

Fig. 1. Jettison locations for pop-up satellite tags deployed on giant bluefin tuna in the Gulf of Maine, 24 September – 6 October, 1997. Insert shows pop-up satellite tag drift patterns after they are released from giant bluefin tuna. Solid circles indicate jettison location and cross hatches indicate daily reporting positions. Scale: 1 deg latitude = 1.85 km.



corded temperature data, along with real-time sea surface temperature, are transmitted for approximately 30 days following jettison. Argos satellites determine the location of the tag and retransmit the data to ground receiving stations. The first 60 average daily water temperature records are obtained during the period immediately following the fish's release. The 61st data record is the average daily water temperature for the day before jettison. Mean values are reported with standard deviations.

Tags were attached to a medical-grade nylon dart using monofilament fishing line. An identification tag was incorporated into the attachment system to allow for collection of a second data record if the fish is recaptured. Twenty giant bluefin tuna were captured (17 by rod and reel, 3 by purse seine), tagged in the dorsal musculature with custom-built tagging applicators alongside the tagging vessels, and released off central New England from 24 September through 6 October, 1997. The total straight fork lengths of four fish (estimated independently by the captain and mate) were 190–200 cm, eight fish were 201–225 cm, and eight fish were 226–263 cm.[3] Tags were programmed to release monthly in groups of five, from late February through July, bracketing the assumed spawning periods in the Gulf of Mexico and Mediterranean Sea. Bluefin reporting locations were plotted on sea surface temperature (SST) fields derived from 9 km resolution Advanced High Resolution Radiometer (AVHRR) NOAA Pathfinder data that were custom processed for 1985–1995 (Arthur Mariano, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, U.S.A., personal communication).

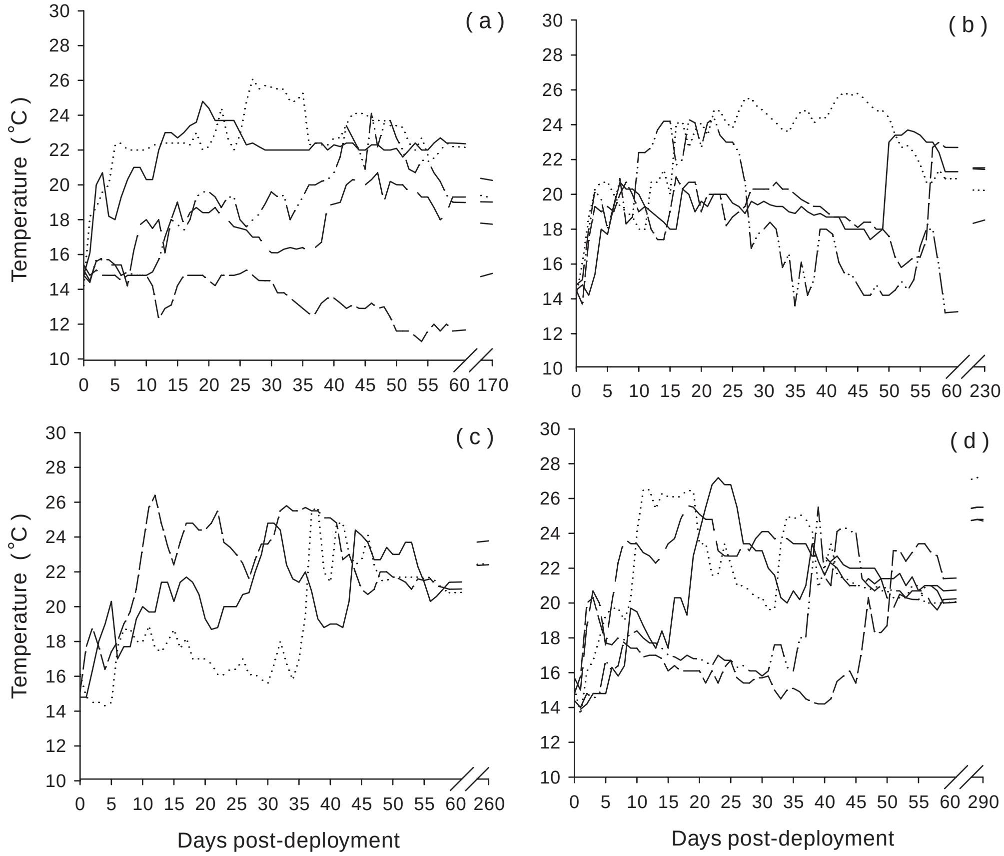
Seventeen tags (85%) successfully released from the fish, and all reported high quality locations and the complete 61 average daily temperature records. At the time of jettison, tagged giant bluefin were located north of 33°N, in the southern temperate and northern subtropical oceanic biogeographic areas along the Gulf Stream and Gulf Stream recirculation region, bounded on the south by the north Sargasso Sea, the Bermuda islands on the west, and the Azores on the east (Fig. 1). Five of seventeen fish were located east of the 45°W ICCAT management line that separates the North Atlantic stock. A continuous eastward travel with time is not apparent, as individuals were present in the easternmost areas in early March as well as in late May and July. There is no apparent trend in distribution by size, as the smallest and largest fish were located along a broad region of the mid-Atlantic. The positions of three individuals that were members of the same school were several hundred miles apart when the tags reported in late February – March.

Because this is the first time that these externally attached tags had been used on long-term deployments, we established that the satellite tags were not jettisoned prematurely by comparing temperature records reported by the tag before and after presumed jettison. The mean coefficient of variation for temperatures before presumed jettison (0.48) was fourfold higher than that occurring after the tags jettisoned (0.14). The drift patterns of tag positions plotted for 30 days after releasing from the fish were primarily circular (Fig. 1 inset). If tags had come off prematurely in the Gulf of Maine, these drift patterns could not reasonably account for their subsequent mid-Atlantic reporting positions.

Sea surface temperatures when the tags jettisoned in late February – March and May–July were 16–19°C and 20–28°C, respectively, and are consistent with climatology records and real-time SSTs from AVHRR archives. The range of mean daily temperatures was 11–27°C (x = 20.4°C ± 5.79). Based on temperature records (Fig. 2), two individuals probably remained in the New England continental shelf area (<16°C) for at least 10 days and one possibly as long as 59 days after tagging, while fourteen apparently traveled to warm Gulf Stream waters within that period. On the day before jettison, mean temperatures for May (20.8 ± 0.61°C), June (23.3 ± 0.80°C), and July (25.6 ± 1.22°C) were considerably warmer

[3] Current bluefin tuna lengths at age estimates (SFL): age 7, 177 cm; age 8, 193 cm; age 9, 207 cm; age 10, 220 cm; age 11, 233 cm; age 12, 244 cm; age 13, 254 cm.

Fig. 2. Mean daily temperatures recorded by pop-up satellite tags deployed on giant bluefin tuna and jettisoned over the following periods: (*a*) 23 February – 5 March, 1998; (*b*) 18–26 May, 1998; (*c*) 19–22 June, 1998; and (*d*) 19–23 July, 1998. The first 60 values are for the 60 days immediately following tagging. Data collection is suspended until the day before jettison, when the tag records the 61st (final) data record.



than the February–March records (17.5 ± 1.07°C). Temperature records from giant bluefin tuna in this study and smaller bluefin tagged in Cape Hatteras (Block et al. 1998) indicate that bluefin experience rapid changes in mean daily temperatures. These gradients could be accounted for by shifts in depth of occurrence and also by travel across fronts at boundary current margins.

The view of bluefin migration indicated by our results differs from the management paradigm that western Atlantic spawning size class bluefin are primarily found in the Gulf of Mexico in late April – June. There are historical accounts of bluefin tuna spawning in the Azores and Canary Islands (Mather et al. 1995), but larvae have not been found there. However, bluefin tuna were consistently documented in the middle and northwest Atlantic in Japanese longline fisheries (Shingu and Hisada 1977) and in the U.S. Bureau of Commercial Fisheries exploratory R/V *Delaware* and *Crawford* cruises in the 1950s–1960s (Mather and Bartlett 1962; Squire 1963). Medium- and giant-sized fish in spawning, near spawning, or recently spent condition were sampled in late spring along the northern boundary of the Gulf Stream off New England (Baglin 1976; Mather et al. 1995). Surprisingly, these observations were not addressed in later studies, perhaps because minimum age of spawning for "western" Atlantic fish remains controversial, and lacking additional confirmation, these views were held in question.

The current paradigm of bluefin reproduction is that spawning occurs in restricted water masses on continental shelves (e.g., edges of the Gulf of Mexico's Loop Current or the Mediterranean Sea), which supposedly support favorable larval tuna habitat (Bakun 1996). Yet strong thermal boundaries, differential advection, and vertical mixing processes are also characteristic of oceanic regions bordered by boundary currents (Olson et al. 1994), and other tunas (e.g., albacore, skipjack, yellowfin) utilize oceanic frontal regions for reproduction (Bakun 1996). Historically, sampling for bluefin tuna has occurred primarily on the continental shelf and not in oceanic regions. In 1985, larval bluefin were found in Gulf Stream water in the South Atlantic Bight, but McGowan and Richards (1989) concluded that the Gulf Stream waters were inappropriate for optimal larval development. Questions then remain as to the disposition of giant bluefin tuna in the mid-Atlantic during the presumed spawning period.

Although we cannot say with certainty that the fish that we tagged were spawning in the mid-Atlantic region, it is a distinct possibility. Most of the tagged fish were within currently accepted spawning sizes, and hydrographic conditions of the summer locations are within SSTs (24–27°C, Richards 1976), salinity, and productivity ranges of Gulf of Mexico spawning grounds. Although entirely speculative at this point, the presence of a mid-Atlantic spawning ground could account for inconsistencies in recent observations regarding the Atlantic bluefin tuna's population biology and migration habits, namely the apparent increase in juvenile and adult age classes on the NW Atlantic fishing grounds (ICCAT, unpublished data, Standing Committee on Research and Statistics, Genoa, Italy, 1998), the decline in numbers of spawners in the Gulf of Mexico, and the consistent failure to find any substantial assemblage of young of the year (age 0s) on the continental shelf. The alternatives that would discount a mid-Atlantic spawning zone include the following: that giant bluefin tuna do not spawn each year, that tagging alters migration behavior, or that all of the tagged fish spawn elsewhere in April or August. Most of these explanations seem unlikely and lack parsimony. Fecundity of bluefin tuna is believed to increase with size (Baglin 1976), and at least six of our tag returns were from individuals estimated to be at least 220 cm SFL. Even if bluefin tuna were to skip a reproductive year, which is not known in the tunas, it is hard to imagine a case where all of the tagged fish (encompassing different age classes) would be on the same reproductive schedule such that none returned to the presumed Gulf of Mexico or Mediterranean spawning areas. Moreover, it seems equally unlikely that disturbance from tagging causes all of the fish to undertake "abnormal" migrations but that all were in the same general direction. Smaller bluefin tuna tagged off Cape Hatteras and at large for up to 90 days had a similar latitudinal distribution along the Gulf Stream margin (Block et al. 1998). An alternative hypothesis that all of the fish spawned in the Gulf of Mexico either in April or August, periods not covered by our tagging results, is unlikely because peak spawning activity and gonadal-somatic index is greatest there in May and June (Richards 1976; Baglin 1976).

The consistency of the locations of tagged giant bluefin tuna during their presumed summer spawning period argues at the very least for reconsideration of current assumptions about migrations, spawning habitat, and stock structure. In a recent analysis of ICCAT tagging data for 1970–1994, only 1% (26 of 21 208) of bluefin tuna released off North America were taken in the eastern Atlantic (Restrepo 1996), yet 29% of the bluefin tagged in this study were located in the eastern management division. These results suggest that mixing across the 45°W management line is significantly higher than the 2–7% range estimated by ICCAT.

The presence of spawning size class fish in the mid-Atlantic, coincident with the presence of other spawning size class fish in the Gulf of Mexico and on the continental shelf off the U.S. and Canada, suggests that the distribution of adult bluefin tuna may be broader than that acknowledged by currently accepted assessments. This study is the first to validate the successful long-term (9.5 month) external attachment of self-releasing tags on giant bluefin tuna. Pop-up archival satellite tags, data-logging tags that record light levels for daily geolocation estimation and can intensively sample temperature and depth, have been succesfully tested and deployed on giant bluefin tuna in the Gulf of Maine in 1998 (M. Lutcavage, unpublished data). These new tags will allow complete reconstruction of migration routes and have the potential to make significant and rapid improvements in our understanding of migration, spawning, stock structure, and population assessments of the North Atlantic bluefin tuna. Such improvements are clearly needed for effective resource conservation and equitable fisheries allocations.

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