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Horizontal and vertical movements and habitat use of the common thresher shark *Alopias vulpinus* in the western North Atlantic

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ABSTRACT: In the western North Atlantic (WNA), the common thresher shark *Alopias vulpinus* is captured by several fisheries, but its population status has not formally been assessed, and its ecology and population structure are poorly understood. A total of 61 pop-up satellite archival transmitting tags were deployed to study the species' horizontal and vertical movement patterns and habitat use in the WNA and to inform the formulation of fishery management policy. Tracking data from 48 individuals ranging from 122 to 259 cm fork length revealed widespread horizontal movements throughout the WNA between northeastern Florida north and east to the Grand Banks of Newfoundland. Seasonal migrations across continental shelf and off-shelf habitats were identified in both juveniles and adults. Tagged common thresher sharks inhabited a wide temperature range in the WNA (−0.5 to 25.6°C), but spent ~90% of their time in waters between 14 and 20°C. Depth distribution ranged from the surface to 1822 m, with ~87% of time spent at depths shallower than 50 m. Deeper depths were achieved during the winter, spring, and fall than during the summer. These results will assist with the identification of important geographic locations of occurrence for both juvenile and adult common thresher sharks, help forecast the effects of environmental change on the species' distribution, and inform the relevant spatial scales for fishery management policies and stock assessment.

KEY WORDS: PSAT · Telemetry · Geolocation · Alopiidae · Stock structure · Pelagic

1. INTRODUCTION

The common thresher shark *Alopias vulpinus* is a circumglobal species that occurs throughout temperate and subtropical waters (Compagno 2001). In the North Atlantic, common thresher sharks are captured by a wide range of coastal and high-seas fisheries (Young et al. 2016, Rigby et al. 2022); however, the species' population status has not been formally assessed, nor is its total catch managed with annual catch limits or international quotas. Despite the lack of formal assessment, there is some evidence of decreasing abundance in multiple regions throughout the North Atlantic during the 1980s–2010s (Ferretti et al. 2008, Young et al. 2016, Lynch et al. 2018), and the species is globally classified as Vulnerable with a declining population trend by the International Union for the Conservation of Nature (Rigby et al. 2022). Given the purported declines in the North Atlantic, the species' late maturity (8–13 yr; Gervelis & Natanson 2013) and low fecundity (2–6 pups biennially; Natanson & Gervelis 2013) in the region,

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and the general vulnerability of the species to overexploitation (e.g. Smith et al. 2008), more focused population assessment and management is warranted. However, such efforts are confounded by the persistent lack of basic ecological data on the species' movements, habitat use, and population structure throughout the Atlantic basin, all of which are key requirements in the formulation of stock assessments and effective fishery management policy.

Much of what is known about common thresher shark ecology in the North Atlantic has been inferred from fisheries-dependent data. Unlike the eastern Pacific Ocean (EPO), where the species has been the focus of extensive conventional and electronic tagging efforts (e.g. Cartamil et al. 2010, 2011, 2016, Kinney et al. 2020), limited tagging data exist from the Atlantic (i.e. n = 2 fisheries-dependent recaptures from 1962 to 2018; Kohler & Turner 2019). Regional assessments of common thresher shark distribution, inferred from catch data in the North Atlantic, indicate the use of both continental shelf and offshore waters in the eastern North Atlantic and Mediterranean Sea (Moreno et al. 1989) and in the western North Atlantic (WNA) off the USA and Canada (Kneebone et al. 2020), and show strong evidence of seasonal migrations and variable habitat use across various life stages. While catch data permit inference into common thresher shark distribution, habitat use, and environmental preferences in the WNA (e.g. Kneebone et al. 2020), these data are only representative of the spatial and temporal extents of where and when the species interacts with fisheries and thus may provide an incomplete assessment of its distribution or movement ecology. Furthermore, the available catch and limited conventional tagging data do not provide detailed information on the habitats (e.g. depth and temperature) that individuals use, thereby precluding the investigation of how environmental conditions may modulate movement ecology (e.g. Skomal et al. 2021) or habitat use (e.g. Braun et al. 2023).

The assessment of the population structure of the common thresher shark in the North Atlantic has been hindered by limited genetic information and the apparent lack of any conventional tag and recapture data showing transoceanic movements. A single genetic study that analyzed mitochondrial DNA demonstrated weak evidence of population differentiation between common thresher sharks sampled in the eastern North Atlantic (France, n = 4 individuals) and the WNA (Gulf of Mexico and US East Coast, n = 44 individuals) and reported low genetic variation within populations, suggestive of lower dispersal in common thresher shark compared to its congeners (Trejo 2005). Based on these findings and the lack of movement data demonstrating trans-Atlantic migrations, the International Council for the Exploration of the Sea (ICES) assumes that 2 common thresher shark stocks exist in the North Atlantic: one comprising individuals in the eastern Atlantic and Mediterranean Sea, and a second inclusive of individuals in the WNA (ICES 2009). However, given the low number of samples for which genetic (n = 48) and conventional tag-recapture data (n = 2) are available, this conclusion remains tenuous (Young et al. 2016). Accordingly, the stock structure assumed by ICES is not recognized by the International Commission for the Conservation of Atlantic Tunas (ICCAT), which performs common thresher shark catch accounting across the entire Atlantic (i.e. the entire ICCAT convention area; Mas et al. 2022) and aggregates these data across member states.

Considering the purported common thresher shark population decline in the WNA (Lynch et al. 2018), continued fishing mortality (Kneebone et al. 2020), and the lack of formal population assessment, a better understanding of the species' ecology and movement is needed to inform the design of future population assessments and to guide management decisions. We used pop-up satellite archival transmitting (PSAT) tags to study the species' movement patterns and habitat use in the WNA in association with this purported stock area. The resulting data yield insights into the species' North Atlantic population structure and will be of use for delineating essential fish habitat (EFH) in US waters as well as for the assessment of the impact of environmental change on the species in the Atlantic and other ocean basins.

2. MATERIALS AND METHODS

2.1. Study design

Tagging activities were conducted over a broad area of the WNA, defined as those waters north of 0° N and west of 40° W, from North Carolina, USA, to Newfoundland, Canada, in waters ranging from the shoreline to 200 km offshore. Tag deployment was performed over as broad an area as possible to achieve the most holistic understanding of common thresher shark movements, migrations, and habitat use in the purported WNA stock area. Tags were deployed by the authors during dedicated research trips, opportunistically by trained volunteer researchers during other research activities, and by charter (US) and commercial (US and Canadian) fishers during their regular fishing activities. Gear types included rod and reel (hook and line), demersal gillnet, and pelagic longline. All tagging was conducted in accordance with the University of Massachusetts Animal Care and Use Committee (protocol 20-10) and the New England Aquarium Animal Care and Use Committee (protocols 2018-07 and 2021-06).

2.2. PSAT tagging

Upon capture, common thresher sharks were outfitted with one of 3 types of PSAT tags (miniPAT, Mk10, or mark–report [mrPAT]; Wildlife Computers). PSAT tags were rigged with a tether consisting of 140 kg monofilament covered with silicone tubing and a titanium dart. The length of the tether (7.5–20 cm) and size of the titanium dart (small or large) were adjusted based on the size of the animal to minimize tag-induced stress and injury. All tags were anchored to the fish by inserting the titanium dart into the dorsal musculature at the base of the dorsal fin. To minimize the chance of post-release mortality, all sharks were left in the water during tagging, and attempts were made to minimize capture-related stress. For each tagging event, the release location (i.e. latitude, longitude), shark size (i.e. fork length [FL], which was estimated due to logistical difficulties obtaining accurate measurements aboard many of the vessels and to minimize boatside handling), sex, and general observations of animal condition (e.g. location of hooking, bodily injury, overt signs of vigor) were recorded.

2.2.1. miniPAT and Mk10

A total of 40 PSAT tags (miniPAT, n = 39; Mk10, n = 1) were deployed on common thresher sharks from 2011 to 2023. Both tag types were programmed to collect high-resolution depth (sensor range: 0–1700 m; sensor accuracy: ±0.05 m), temperature (sensor range: −20 to 50°C; sensor accuracy: ±0.05°C), and light level data over a fixed deployment period of 270 d (all miniPAT) or on a specific calendar date (the single Mk10, 15 January 2012). After detaching from the animal, summarized representations of the archived data were transmitted through the Argos satellite array, including daily time-at-depth histograms (bin limits: <2, 10, 25, 50, 75, 100, 200, 400, 600, 800, 1000, and 2000 m), daily time-at-temperature histograms (bin limits: 2–26 at 2°C increments), depth–time series data (10 min resolution), temperature–time series data (10 min resolution), light level data (twilight, sunrise or sunset), and daily minimum and maximum depth and temperature. If tags were physically recovered, the full archive of depth, temperature, and light data were available at their native sampling resolution (0.067 and 0.3 Hz miniPAT; 0.1 Hz Mk10).

2.2.2. mrPAT

A total of 21 mrPAT tags were deployed from 2017 to 2021. The mrPAT tags were programmed to detach on a specific calendar date between 1 December and 1 April and transmit their location to Argos satellites to provide a fishery-independent 'recapture' location. This programming scheme was used to generate data on animal presence (i.e. relocation) during the winter months. Each tag transmitted daily minimum and maximum temperature readings (sensor range: −20 to 50°C; sensor accuracy: ±0.05°C) as well as daily maximum change in tilt (via an accelerometer sensor) over the 100 d period preceding pop-up (i.e. the last 100 d of the deployment period).

2.3. Data analysis

Tagged common thresher sharks were assigned a life stage using published estimates of length at 50% maturity for individuals from the WNA (Natanson & Gervelis 2013). Males from 101 to 187 cm FL and females from 101 to 215 cm FL were classified as juveniles. Males ≥188 cm FL and both females and sharks of unknown sex ≥216 cm FL were considered adults. To examine temporal trends in distribution and habitat use, seasons were classified as winter (January–March), spring (April–June), summer (July–September), or fall (October–December). All analyses were performed in R (v.4.4.3; R Core Team 2025). Maps and figures were created by using the tidyverse collection of packages (v.2.0; Wickham et al. 2019) and the 'sf' package (v.1.0-19; Pebesma & Bivand 2023) in R.

2.3.1. Horizontal movements and distribution

Geolocation of the miniPAT and Mk10 PSAT tag data was conducted using the R package 'HMMoce' (Braun et al. 2018). This gridded hidden Markov model approach compares diverse tag-based observations against remote sensing and data-assimilating oceanographic model outputs to generate likelihoods of a tagged individual's location at each time step of its deployment. At 24 h intervals, we calculated 4 separate likelihoods: (1) light-based latitude and/or longitude determined by a threshold-based algorithm (Hill & Braun 2001, implemented in the GPE2 software, Wildlife Computers), (2) sea surface temperature (SST) generated from comparing tag-based SST values against the National Oceanic and Atmospheric Administration (NOAA) 0.25° Daily Optimum Interpolation SST (OISST) climate data record (Reynolds et al. 2007, Banzon et al. 2016), (3) ocean heat content (OHC; Luo et al. 2015) generated from comparing integrated tag-based profiles of depth and temperature against those from the 1/12° Global Ocean Physics Reanalysis (GLORYS, Lellouche et al. 2018), and (4) bathymetry flexibly based on comparison of the tag-recorded maximum depth against the SRTM30_PLUS data set (Becker et al. 2009). The bathymetry likelihood was formulated to either act as a depth filter or identify a bottom depth contour, depending on the vertical movement behavior of the shark. The depth filter used a binary likelihood that precluded the fish from occurring in waters with bottom depth shallower than the daily maximum depth (Galuardi et al. 2010). The bottom contour-based likelihood used the daily maximum depth as the mean bottom depth contour that the fish likely occupied (Pedersen et al. 2008) and was formulated using a Gaussian distribution. Given that the bottom depth contour likelihood results in a significantly more constrained bathymetry likelihood for deployment days with likely bottom association, it can improve geolocation accuracy (Arostegui et al. 2024b). We identified days of likely bottom association as those for which the daily maximum depth was <50 m for an uninterrupted, extended series of consecutive days. This depth cutoff was chosen based on the frequent capture of common thresher sharks in bottom gillnet and trawl fisheries operating in waters 50 m or shallower (Kneebone et al. 2020). All light-based likelihoods were visually checked and filtered to exclude spurious estimates, and all likelihood grids (i.e. light, SST, OHC, and bathymetry) were resampled to 0.08° spatial resolution.

The resulting observation likelihoods were combined into daily overall likelihoods and then convolved with a diffusive movement kernel representing a single behavior state. Movement parameter estimation used bound-constrained optimization (Byrd et al. 1995). The daily posterior likelihood surfaces were summed for each shark to yield their time-integrated spatial utilization distributions (UDs) throughout the overall deployment as well as for each month. The most probable track for each deployment was calculated with the Viterbi method, a global decoding solution that improves daily location estimates derived from the posterior probability surfaces (Nielsen et al. 2023). In the event of model convergence issues, the geolocation was re-run excluding the OHC likelihood. Similarly, if an initial track estimate crossed land due to straddling of complex topography by the movement kernel (e.g. Long Island, New York), we applied an expanding kernel method (n = 8 'mini-expansions' per time step) to improve posterior probability surfaces near these features on the corresponding days before re-generating the track (Nielsen et al. 2023). Seasonal UDs were calculated by summing daily UDs in each season for each shark and then taking the mean across all sharks tracked in the season. The total distance (km) of each shark's most probable track was calculated using the 'st_distance' function in the 'sf' package (Pebesma & Bivand 2023).

Relocation (i.e. pop-up location or recapture) data obtained from PSAT tags were plotted in relation to the tagging location, month of tagging, and month of reporting for each animal. For each tag, the minimum linear displacement distance (km) between tagging and reporting locations was calculated using the 'st_distance' function in the 'sf' package (Pebesma & Bivand 2023). Time-at-liberty was calculated as the date of tagging to the date of recapture or reporting. For mrPATs that detached prematurely, the date of detachment was identified by examining daily minimum–maximum temperatures and daily maximum change in tilt values.

2.3.2. Vertical movements, depth and temperature occupancy

Daily (24 h) binned time-at-depth and time-at-temperature histogram data collected by miniPAT and Mk10 tags were aggregated by month and plotted for juvenile and adult individuals. Summary statistics for percent of time-at-depth and time-at-temperature bins were calculated for all animals as well as for juveniles and adults, sex, month, season, and over days when individuals had a maximum depth deeper and shallower than 200 m. Depth and temperature time series data from miniPAT and Mk10 tags, including the full archives from recovered tags, were compiled by Julian day and plotted in aggregate to visualize daily, monthly, and seasonal trends. Plots were bounded by the daily minimum and maximum temperature data observed on each day of the year across all 3 PSAT models. Boxplots were used to examine trends in temperature across depth bins evident in the time-at-depth data. In some plots, bin widths were consolidated for ease of interpretation (i.e. depth: <25, 25–50, 50–100, 100–200, 200–600, and >600 m; temperature: <6, 6–10, 10–14, 14–18, 18–22, and >22°C).

3. RESULTS

Tagged common thresher sharks (n = 61) ranged in estimated size from 122 to 259 cm FL (mean ± SD: 181 ± 32 cm) and included 46 juveniles (35 females, 6 males, 5 individuals of unknown sex), 13 adults (4 females, 8 males, 1 individual of unknown sex), and 2 individuals of unknown sex and life stage (Table 1). A total of 50 tags (31 of 40 miniPAT, 1 of 1 Mk10, and 18 of 21 mrPAT) reported via the Argos satellite network. Of these, 21 tags (34% of all tag deployments) completed their programmed deployment period (11 miniPAT, 10 mrPAT) and 29 (47% of all tag deployments) detached prematurely (20 miniPAT, 1 Mk10, 8 mrPAT). Premature release occurred due to physical breaking of the tag's nosecone pin (8 miniPAT; Lam et al. 2020), malfunction of the tag's pressure sensor (4 miniPAT) (i.e. release was initiated because the tag software algorithm detected a constant depth or a depth value that exceeded the maximum allowed cutoff), post-release mortality (3 mrPAT), and for unknown reasons (8 miniPAT, 1 Mk10, and 5 mrPAT). A total of 11 tags (18% of all deployed tags, 8 miniPAT, 3 mrPAT) did not report via the Argos satellite network. However, 2 non-reporting tags (1 miniPAT and 1 mrPAT) were physically recovered and provided usable data. The miniPAT tag was found washed ashore with its antennae missing (the potential reason why no Argos transmissions were received), and the mrPAT tag was found attached to the shark upon its recapture 457 d after deployment (the recapture location was subsequently used as the 'reporting location' to infer horizontal movement; note that mrPAT tags do not store raw data archives). In total, viable data spanned 8463 total tracking days from 48 individuals (30 miniPAT, 1 Mk10, 17 mrPAT), including 9 miniPAT tags and 1 Mk10 tag that were physically recovered and downloaded.

3.1. Horizontal movement and distribution

Geolocation and horizontal displacement data indicated tagged common thresher sharks exhibited extensive movements throughout the WNA from ~27° to 47° N latitude and from 81° to 37° W longitude, spanning continental shelf and off-shelf waters (Fig. 1). Total horizontal distance traveled during geolocation tracks ranged from 389 to 5812 km (mean ± SD: 3765 ± 1947 km) over periods of 8–270 d (mean ± SD: 178 ± 100 d). Straight-line horizontal distances between tag and reporting locations ranged from 15 to 2354 km (648 ± 432 km).

Geolocation tracks and horizontal displacement trajectories indicated strong seasonal movements that included along-shelf (i.e. north–south) and on-shelf–off-shelf movements (Figs. 1 & 2). Movements and distribution were similar between juveniles and adults and between males and females (Fig. A1 in the Appendix); thus, trends are presented relative to all tracked individuals. During the winter, UDs were largest and indicated 2 distinct regions of concentrated activity: a vast area in the Slope Sea and northern portion of the Gulf Stream beyond the 200 m isobath ranging from the Scotian Shelf south and west to North Carolina from 35° to 40° N latitude and from 75° to 60° W longitude, and in continental shelf waters <200 m in depth along the US East Coast from North Carolina to northeastern Florida (Fig. 3). In spring, the core UD was centered in continental shelf and Slope Sea waters off the US East Coast from North Carolina to New Jersey, and several individuals used the southern extent of Georges Bank. The summer UD indicated peak use of continental shelf waters from New Jersey through Massachusetts, extending throughout the Gulf of Maine and along the shelf bathymetric break south of Georges Bank and the Scotian Shelf. In fall, UDs indicated both eastward movement along the shelf bathymetric break towards the Grand Banks of Newfoundland and southward migration in continental shelf waters from Massachusetts to northeastern Florida.

3.2. Vertical movements, depth and temperature occupancy

Common thresher sharks occurred from the surface to depths of 1822 m and in water temperatures from −0.5 to 25.6°C (Fig. 4). Individuals tagged with miniPAT and Mk10 PSAT tags collectively spent ~85% of time between 2 and 50 m, 2% of time deeper than 200 m, 87% of the time in water temperatures between 12 and 20°C, and 99% of the time in temperatures from 8 to 22°C (Fig. 5). Juveniles and adult individuals showed no apparent selection for, or segregation by, depth and temperature across sexes, except for tagged adult males, which spent more time at depths >50 m (26%, n = 6 individuals) than adult females (5%, n = 3 individuals). On days when tracked sharks

Table 1. Metadata from 61 common thresher sharks tagged with pop-up satellite archival transmitting tags in the western North Atlantic. FL: estimated fork length; CD: completed deployment; DNR: did not report; PR: premature release; PRM: post-release mortality. Dates are given as mm/dd/yy

Tag type	Sex	FL (cm)	Life stage	Tagging Date	Tagging °N	Tagging °W	Reporting Date	Reporting °N	Reporting °W	Days deployed	Tag status
Mk10	F	220	A	6/16/11	40.23	67.88	10/17/11	43.92	66.68	123	PR[a]
miniPAT	M	203	A	7/2/17	39.18	70.50	3/5/18	30.40	81.20	246	PR[b]
miniPAT	U	213	U	7/8/17	43.20	69.67					DNR
miniPAT	F	152	J	8/9/17	40.93	71.81	4/26/18	32.85	77.94	260	PR
miniPAT	F	168	J	8/9/17	40.93	71.82	4/14/18	35.61	75.34	248	PR[b]
miniPAT	U	152	J	8/9/17	40.94	71.82					DNR
miniPAT	F	152	J	8/10/17	40.93	71.82	5/8/18	37.04	75.72	270	CD[a]
miniPAT	F	152	J	8/10/17	40.93	71.82	5/12/18	38.32	74.35	270	CD
miniPAT	F	168	J	8/10/17	40.93	71.83	5/9/18	35.23	75.47	270	CD
miniPAT	M	152	J	8/10/17	40.93	71.82	9/13/17	40.83	71.94	35	PR
miniPAT	F	152	J	8/14/17	40.92	71.89					DNR
miniPAT	F	168	J	8/14/17	40.98	71.75	10/16/17	40.52	73.60	64	PR[a]
miniPAT	F	183	J	8/15/17	40.99	71.75	5/13/18	35.37	75.28	270	CD
miniPAT	F	168	J	8/15/17	41.00	71.75					DNR
miniPAT	F	183	J	8/16/17	40.98	71.75	9/22/17	40.22	73.85	37	PR[a]
miniPAT	F	203	J	9/28/17	43.22	51.31	2/4/18	37.21	44.12	130	PR[b]
miniPAT	F	213	J	7/31/18	40.98	71.72					DNR
miniPAT	F	198	J	9/3/18	40.89	70.35	6/1/19	39.15	74.52	270	CD
miniPAT	M	221	A	9/30/18	45.17	48.23	5/12/19	38.82	74.98	224	PR[ab]
miniPAT	F	244	A	8/6/19	43.36	70.12	9/10/19	40.65	71.97	35	PR[c]
miniPAT	M	163	J	8/11/19	43.38	70.07	8/14/19	42.18	70.55	3	PR[ac]
miniPAT	F	198	J	8/16/19	40.98	70.51	5/13/20	35.45	75.26	270	CD
miniPAT	F	183	J	8/16/19	40.97	70.53					DNR
miniPAT	M	244	A	9/27/19	43.35	60.97	6/24/20			270	DNR[d]
miniPAT	M	216	A	10/15/19	43.86	48.28	4/17/20	39.99	52.17	186	PR[b]
miniPAT	U	183	J	10/2/20	43.59	59.44	6/30/21	39.14	71.66	270	CD
miniPAT	U	213	U	4/17/21	35.70	74.84	12/31/21	35.99	74.87	259	PR[b]
miniPAT	M	213	A	4/17/21	35.70	74.84					DNR
miniPAT	U	229	A	6/29/21	43.38	70.15	3/27/22	31.58	80.96	270	CD
miniPAT	U	152	J	9/1/21	44.16	58.30	9/21/21	40.36	67.24	21	PR
miniPAT	F	152	J	9/10/21	41.38	71.34	11/29/21	35.55	74.97	81	PR
miniPAT	F	259	A	10/3/21	43.50	69.98	6/30/22	40.56	73.87	270	CD[a]
miniPAT	M	213	A	8/8/22	41.40	71.43	5/6/23	36.20	75.21	270	CD
miniPAT	F	199	J	9/3/22	41.12	71.24	10/20/22	41.11	72.05	47	PR[ac]
miniPAT	F	183	J	9/10/22	41.32	61.47	3/7/23	35.62	55.53	179	PR[b]
miniPAT	F	183	J	9/10/22	41.38	71.37	6/8/23	39.48	74.21	270	CD
miniPAT	F	168	J	9/10/22	41.37	71.35	1/25/23	36.26	74.32	138	PR
miniPAT	U	183	J	8/16/23	43.39	70.27	10/22/23	41.25	71.09	68	PR[ab]
miniPAT	F	229	A	9/4/23	41.38	71.34	3/18/24	32.47	79.19	197	PR
miniPAT	M	200	A	9/13/23	43.66	69.62	10/18/23	40.36	73.56	35	PR[c]
mrPAT	F	213	J	8/10/17	40.93	71.82	2/1/18	39.74	56.24	175	CD
mrPAT	F	137	J	8/15/17	40.98	71.75	3/15/18	36.06	74.67	212	CD
mrPAT	F	152	J	8/15/17	40.97	71.78	8/16/17			1	PRM
mrPAT	M	137	J	8/15/17	40.97	71.78	8/17/17			2	PRM
mrPAT	F	213	J	8/15/17	41.02	71.74	12/15/17	35.83	75.44	122	CD
mrPAT	F	168	J	8/15/17	40.97	71.72	12/1/17	37.50	75.35	108	CD
mrPAT	M	122	J	8/15/17	41.00	71.75					DNR
mrPAT	F	168	J	8/16/17	40.96	71.75	12/7/17	35.71	75.02	113	PR
mrPAT	F	168	J	7/31/18	40.98	71.72	1/1/19	35.76	75.30	154	CD
mrPAT	U	150	J	8/5/18	40.97	71.77					DNR
mrPAT	F	140	J	8/6/18	40.97	71.75	2/17/19	35.95	74.85	195	CD
mrPAT	F	150	J	8/6/18	40.97	71.76	3/1/19	35.90	75.10	207	CD
mrPAT	M	122	J	8/6/18	40.97	71.76	11/6/19	39.72	74.04	457	DNR[e]
mrPAT	F	137	J	8/6/18	40.97	71.76	1/15/19	35.25	75.16	162	CD
mrPAT	F	198	J	8/6/18	40.97	71.76	2/15/19	36.44	74.96	193	CD
mrPAT	F	137	J	8/10/18	40.87	71.82	11/27/18	35.83	75.36	109	PR
mrPAT	F	183	J	8/10/18	40.88	71.82	8/11/18			1	PRM
mrPAT	M	173	J	10/5/19	41.86	70.34	1/11/20	36.48	75.72	98	PR
mrPAT	F	200	J	8/25/20	40.95	70.51	9/2/20	40.44	71.69	8	PR
mrPAT	M	200	A	7/31/21	41.35	71.37	1/1/22	35.79	75.40	154	CD
mrPAT	F	152	J	9/1/21	41.36	71.33	1/12/22	35.73	75.31	133	PR

[a]Tag was recovered; [b]Tag released due to nosecone pin break; [c]Tag released due to a pressure sensor malfunction; [d]Tag was recovered with antenna missing; [e]Shark was recaptured with tag still attached

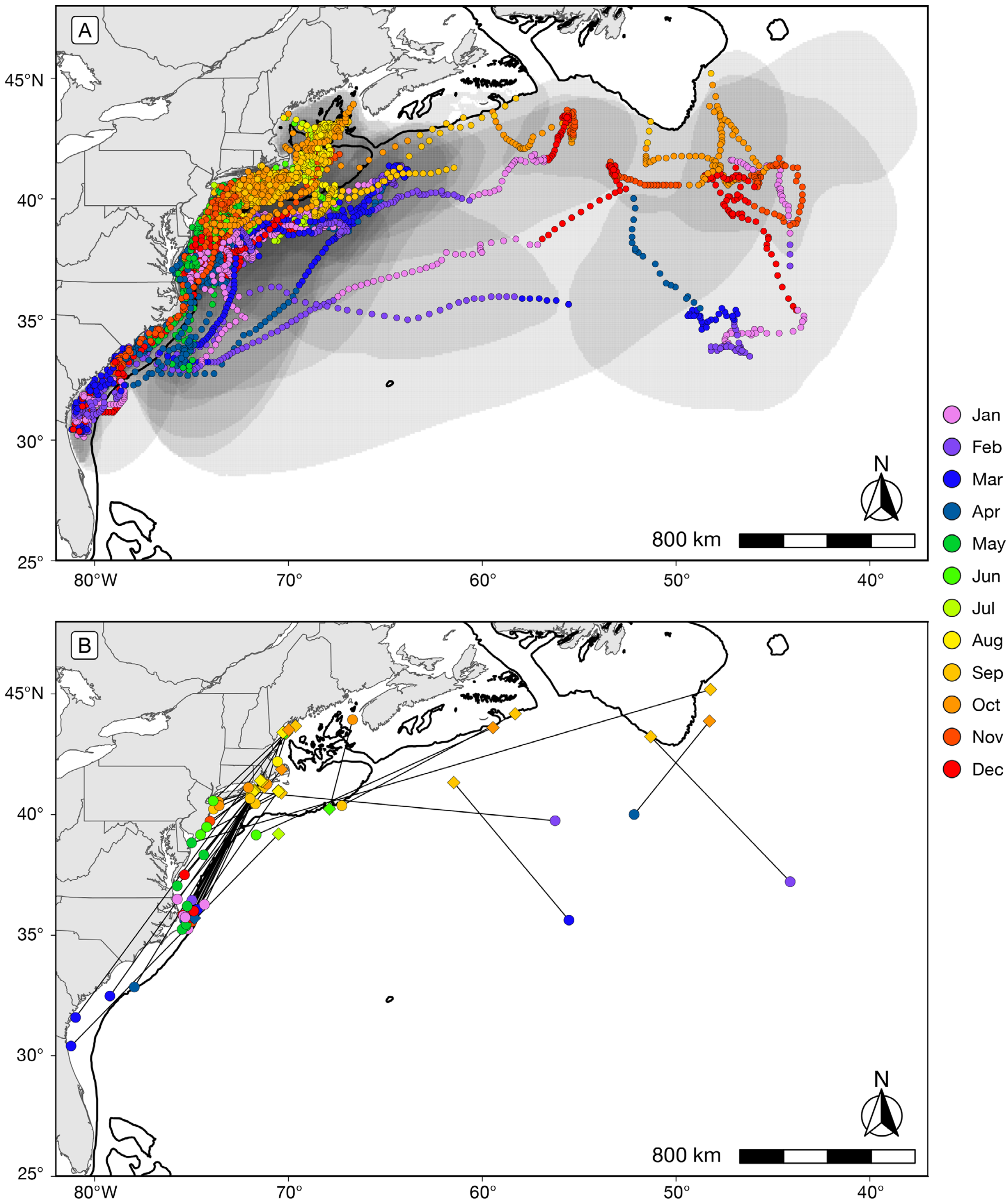

Fig. 1. (A) Most probable geolocation tracks generated for 31 common thresher sharks and (B) straight-line horizontal displacement between tagging (diamond) and reporting (circle, pop-up or recapture) location for 48 PSAT tags (17 mrPAT, 30 miniPAT, 1 Mk10) deployed from 2011 to 2023. Colored circles in (A) represent daily estimated positions by month; light grey shaded area: 95% utilization distribution associated with each track. In (A,B), events are color-coded by the month in which they occurred. Solid black line in (A) and (B) represents the 200 m isobath

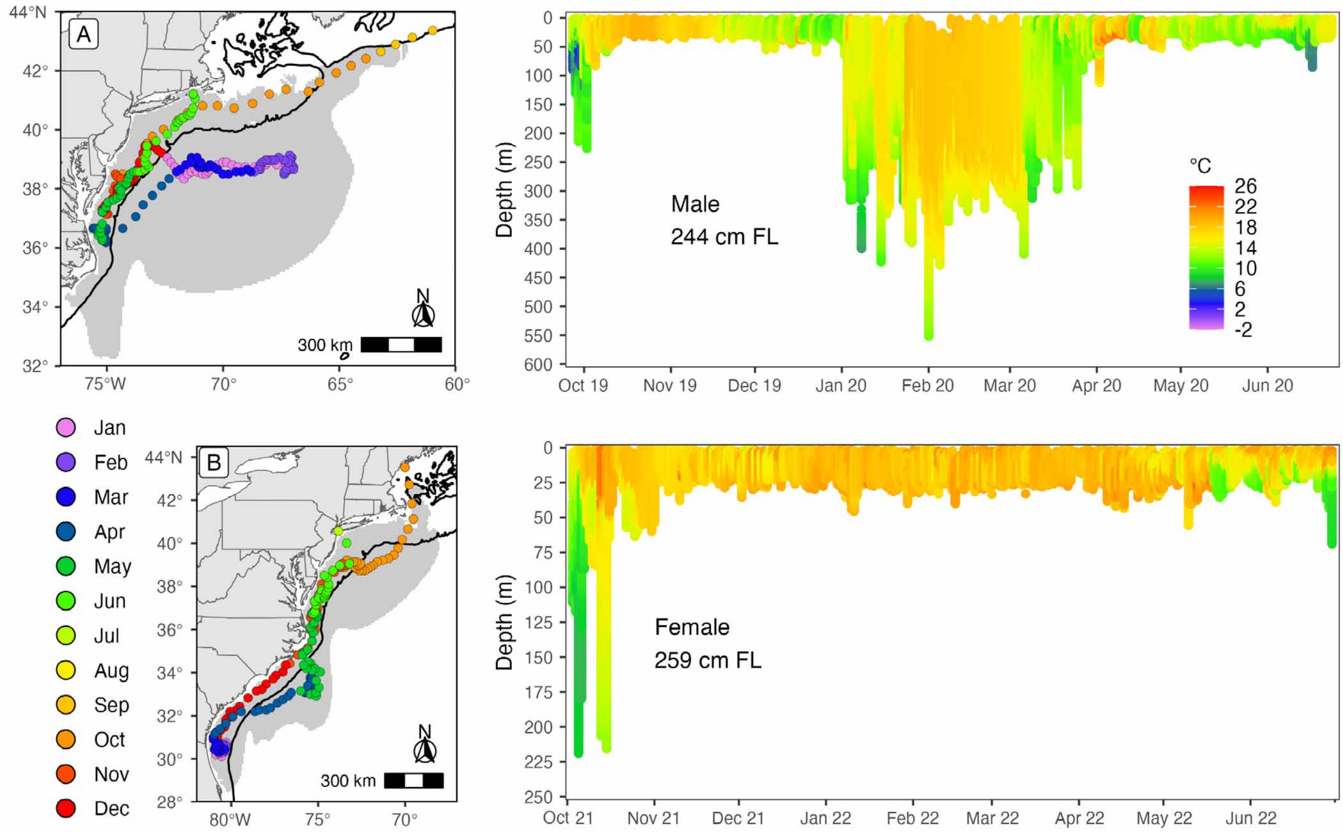

Fig. 2. Example most probable geolocation tracks and associated temperature-at-depth time series data for 2 adult common thresher sharks that exhibited (A) winter residency in off-shelf waters and (B) winter residency along the southeastern USA. Note that both sexes overwintered in off-shelf waters and along the southeastern USA. The monthly location legend and temperature scale bar are shared among both (A) and (B). Note the difference in depth range between (A) and (B). Light grey shaded area: 95% utilization distribution; solid black line: 200 m isobath. FL: fork length

had a maximum depth >200 m (i.e. were assumed to be off the continental shelf [hereafter off-shelf]), on average they spent ~31 ± 9% (mean ± SD) of time in the upper 50 m of the water column. By contrast, on days when common thresher sharks had a maximum depth of <200 m (i.e. were assumed to be on the continental shelf [hereafter on-shelf]) they spent an average of 92 ± 17% of the time in the upper 50 m of the water column (Fig. 6). On days when individuals were off-shelf, on average sharks spent more time in waters cooler than 16°C, but the total amount of time spent between 12 and 20°C was nearly equal across on-shelf (88 ± 22%) and off-shelf (85 ± 15%) habitats (Fig. 6).

Tagged common thresher sharks occupied a wide temperature range from the surface to depths up to 600 m due to their occurrence in locations with both a heavily stratified and well-mixed water column (Figs. 2 & 7). The warmest water temperatures (>24°C) were experienced from the surface down to 50 m, and the coldest temperatures (<4°C) occurred at depths from 25 to 200 m. The median temperature occupied in depth bins from the surface to 600 m ranged from 14 to 20°C, while median temperatures experienced from 600 to 1800 m were between 4 and 6°C. The coldest water temperatures recorded during the study originated from a single adult male during the 2 weeks following its tagging near the Grand Banks of Newfoundland, Canada, in October 2018. During this period, the shark regularly dove to depths between 150 and 325 m and repeatedly encountered water temperatures from −0.5 to 2°C at depths between 50 and 150 m, returning to depths shallower than ~30 m and water temperatures from 15 to 20°C between dives.

Monthly and seasonal patterns were evident in both depth and temperature occupancy. Tagged sharks were present in epipelagic depths (<200 m) in all months but exhibited movement into mesopelagic depths (between 200 and 1000 m) in all months except May and June, and used the upper bathypelagic (1000–1800 m) between September and February (late summer through winter; Figs. 4 & 5). On average, in winter and fall, individuals spent a greater amount of time (13–31%) deeper than 50 m compared to spring and summer (1–8%) and more time in meso-

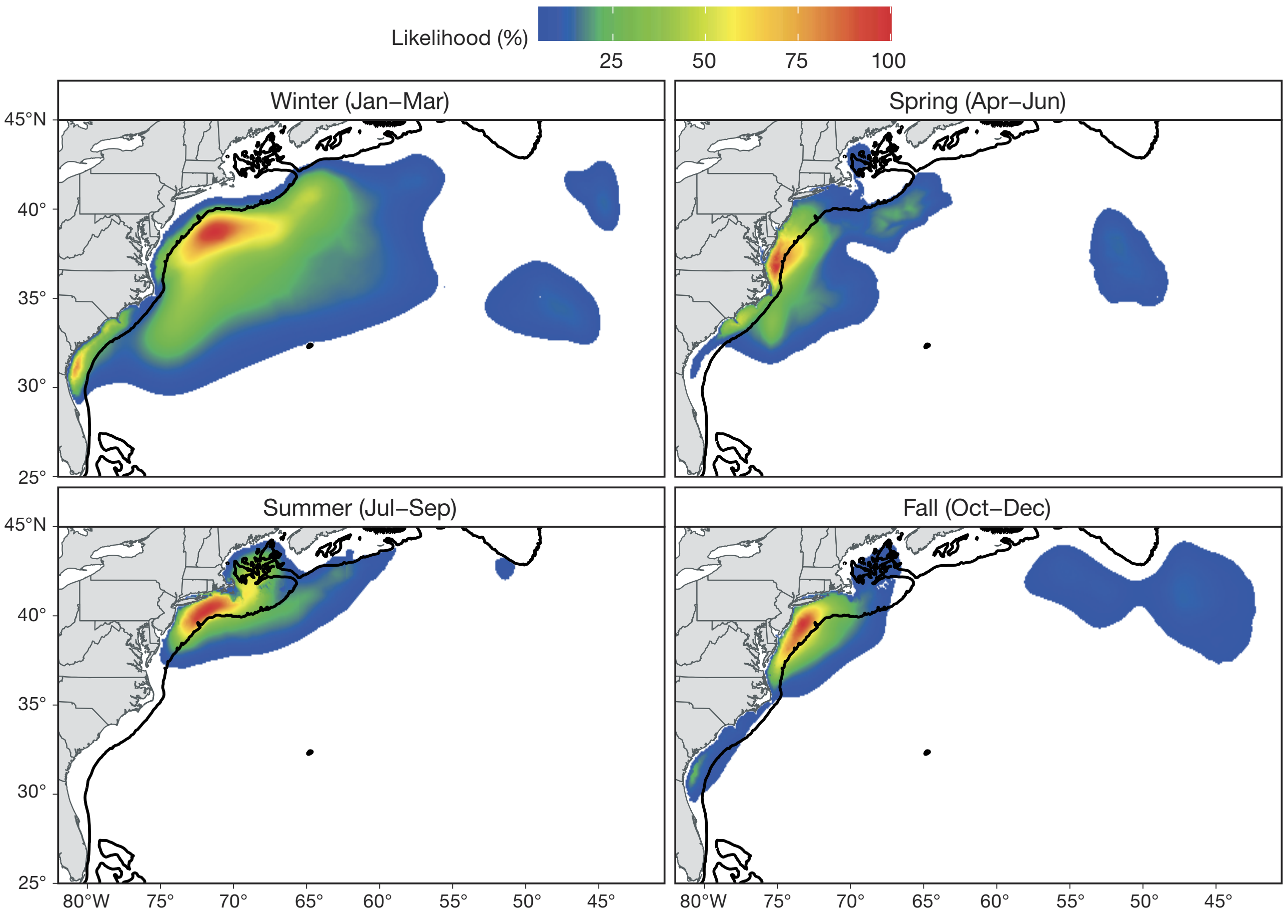

Fig. 3. Seasonal utilization distribution of 31 common thresher sharks (152–259 cm fork length) estimated from geolocation tracks. Tags were deployed between 2011 and 2023. Warmer likelihood colors indicate areas of heightened occurrence. The solid black line represents the 200 m isobath

pelagic and bathypelagic depths (1–9%) compared to spring and summer (0–1%). Many individuals transitioned between epi-, meso-, and bathypelagic habitats periodically throughout the year, while others remained in epipelagic, on-shelf waters throughout their migration (Fig. 2). Tagged sharks also ventured into the coldest waters from September through February (late summer through late winter; minimum temperature range: −0.5 to 3.6°C) (Fig. 4). However, the median and maximum temperature (22.7 to 25.6°C) occupied across all months was relatively consistent (Fig. 8).

4. DISCUSSION

Data obtained with PSAT tags suggest that both juvenile and adult common thresher sharks of both sexes exhibit widespread horizontal movements throughout the WNA and make seasonal migrations that involve the use of continental shelf and deep off-shelf habitats. The data also indicate that while common thresher sharks inhabit a wide temperature range in the WNA (from −0.5 to 25.6°C), individuals in this study spent nearly 90% of their time in waters between 14 and 20°C. Collectively, PSAT tag data enhance the ability to more accurately and completely identify important geographic locations of occurrence (e.g. EFH) for the juvenile and adult life stages, forecast the effects of environmental change on the species' distribution (e.g. Braun et al. 2023), as well as inform the relevant spatial scales for fishery management policies and stock assessment.

4.1. Seasonal distribution and horizontal movement patterns

The synergy of fisheries-independent (i.e. PSAT tag-derived) and fisheries-dependent (e.g. catch records; Kneebone et al. 2020) data indicates that common thresher shark migration in the WNA involves move-

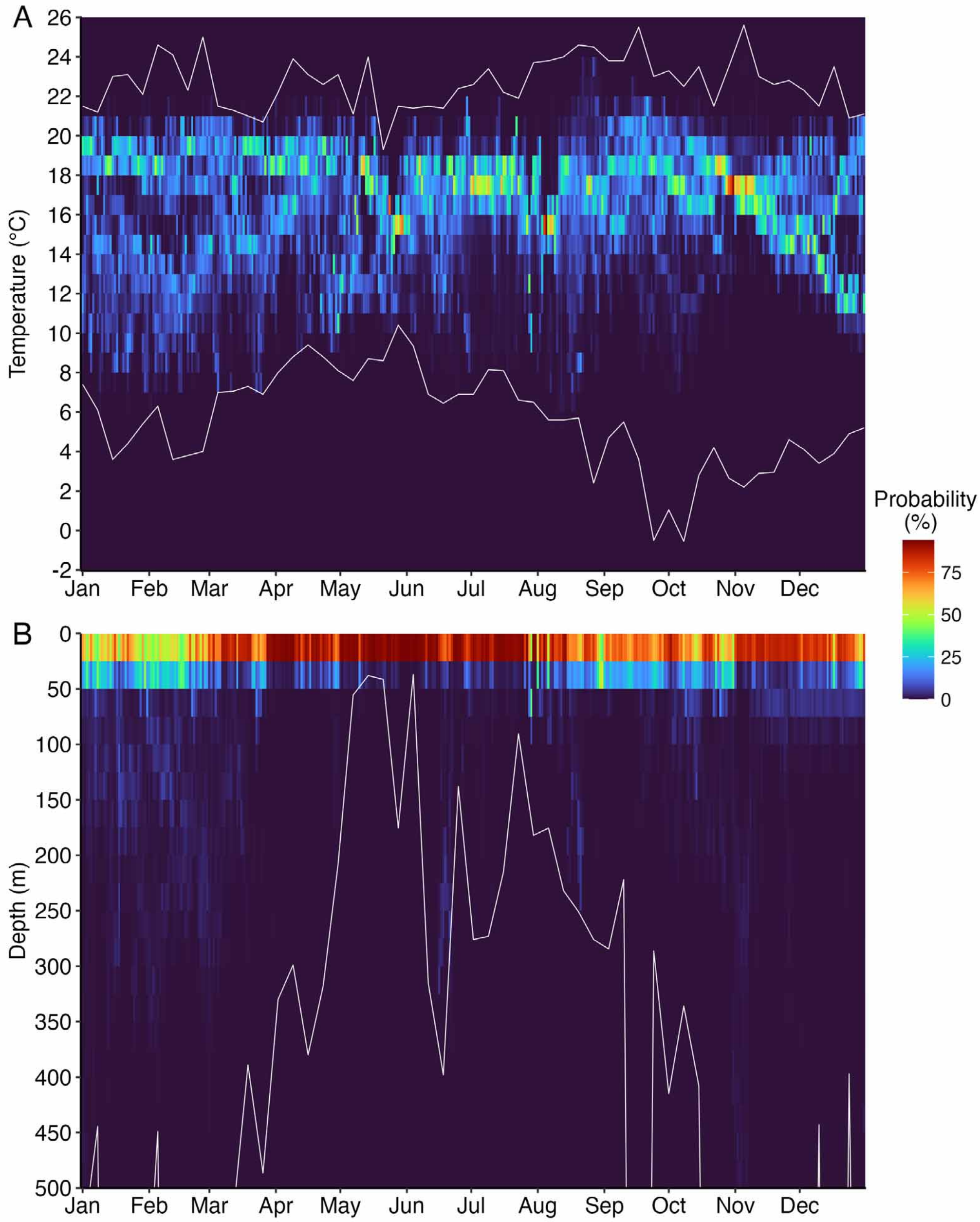

Fig. 4. Probability distributions of (A) temperature and (B) depth occupied by 33 common thresher sharks by day of year between 2011 and 2023. White lines represent the weekly minimum and maximum temperature or depth (maximum only) observed across all dates. The depth plot is truncated at 500 m to improve resolution at depths most occupied (0–50 m)

ments concentrated primarily in inshore, on-shelf habitats (<200 m) of the northeastern USA during warmer months (spring through fall) and a more expansive range throughout off-shelf habitats of the Slope Sea and northern Sargasso Sea, as well as on-shelf habitats of the southeastern USA during winter. Despite the existence of catch records from the Gulf of Mexico in the US pelagic longline fishery and Mexican artisanal fisheries (Castillo-Géniz et al. 1998), none of the tagged individuals moved into this region. However, given the general paucity of catch records in the Gulf of Mexico (see Fig. 4 in Kneebone et al. 2020) and the potential for misidentification between common thresher shark and bigeye thresher *Alopias superciliosus* in this region (Castro 2011), it appears that the common thresher shark exhibits limited movement into and/or occurrence in the Gulf of Mexico.

Both PSAT tag and catch data indicate that common thresher shark migrations along the east coast of North America primarily occur in continental shelf

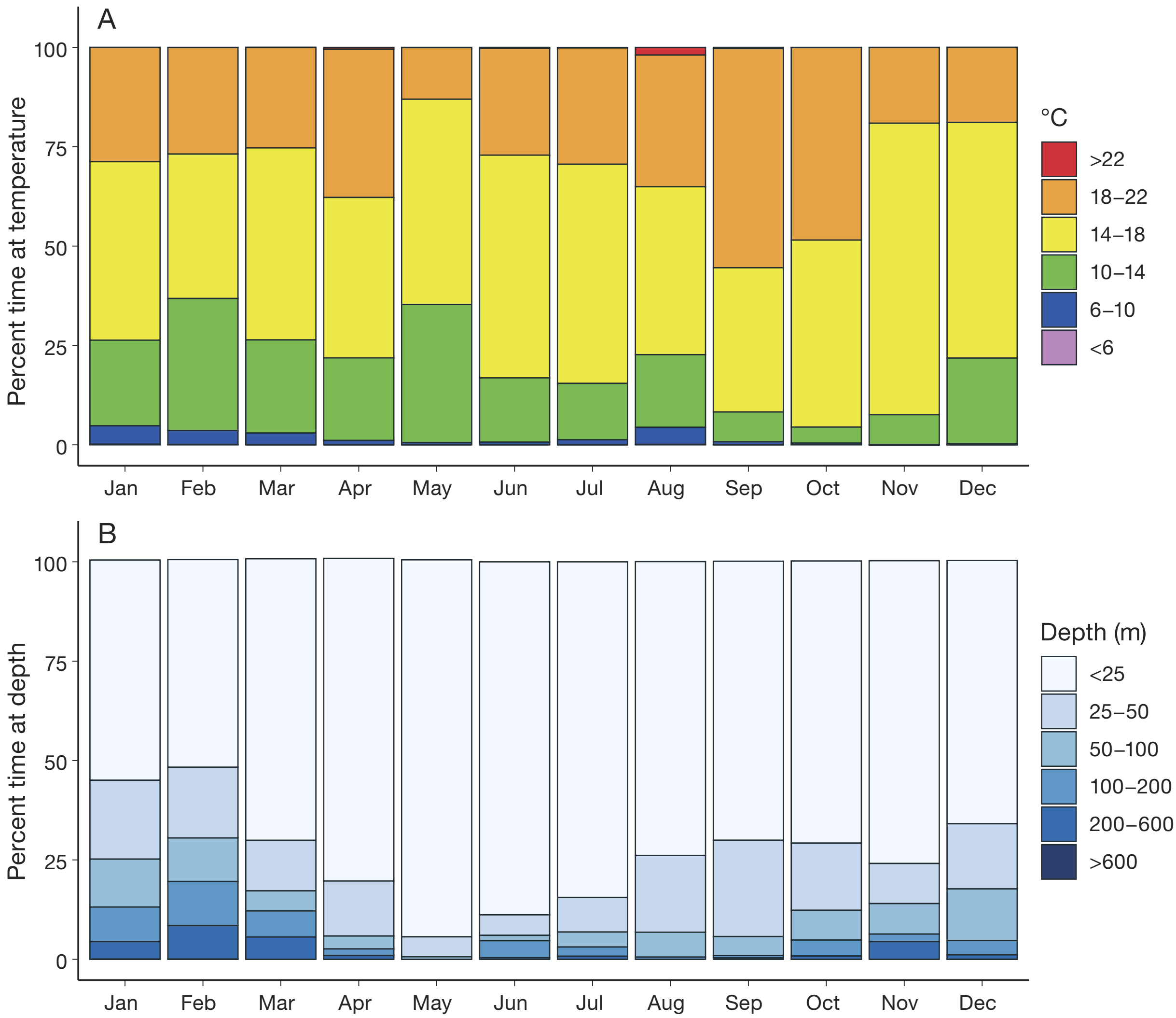

Fig. 5. Aggregated monthly percent time at (A) temperature and (B) depth occupied by 32 common thresher sharks (152—259 cm fork length) tracked between 2011 and 2023

waters of <200 m. However, PSAT tag tracks from several individuals indicated that migratory movements also occur in off-shelf waters, often in association with the Gulf Stream, between North Carolina east to the Grand Banks of Newfoundland. This differential migration pattern involving on-shelf and off-shelf waters is related to the occupancy of 2 distinct habitats by both juvenile and adult common thresher sharks of both sexes during the late fall through early spring (i.e. December through April). For example, while some individuals overwintered in close association with continental shelf waters off the southeastern USA from North Carolina to northeastern Florida, others remained distributed off-shelf over a vast area spanning from the bathymetric shelf break off the Mid-Atlantic region of the USA (southern New Jersey to northern North Carolina) east to roughly 40° W longitude during the same period. Individuals that overwintered off the southeastern USA generally remained in shelf waters of depths <50 m and exhibited more localized movements that sometimes included forays off the continental shelf. By contrast, individuals that were present in off-shelf waters from December through April exhibited variable horizontal movement patterns, including protracted, directed westward movements within or along the northern edge of the Gulf Stream and more localized movements in association with seamount areas south of the Grand Banks of Newfoundland (i.e. Fogo Seamounts and Corner Rise Seamounts). Consequently, the winter core UD of geolocated sharks spanned a vast area, with the greatest concentration of activity occurring off the northeastern USA in Slope Sea waters. It is unclear what biotic or oceanographic factors dic-

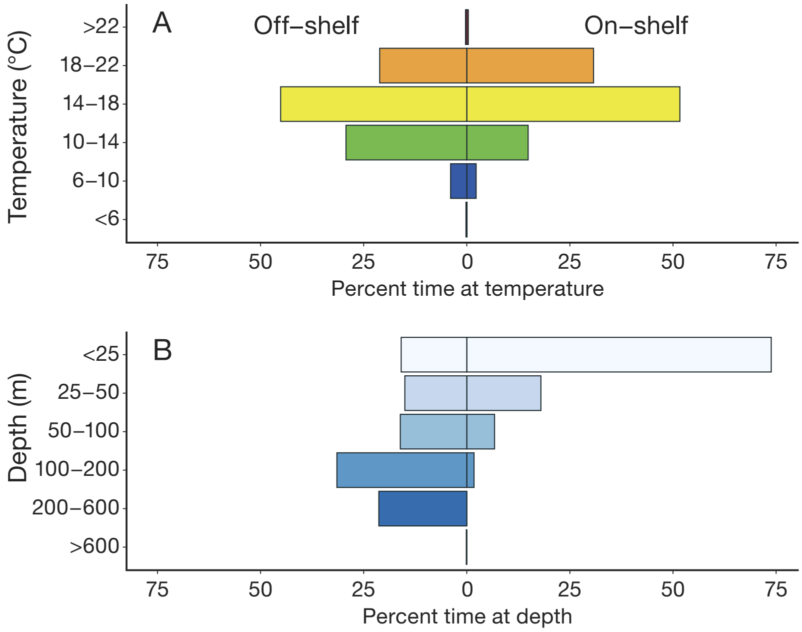

Fig. 6. Percent time at (A) temperature and (B) depth across days when common thresher sharks (n = 33, 152–259 cm fork length) inhabited continental shelf (on-shelf: <200 m, 4030 total days) and off-shelf (>200 m, 478 total days) waters between 2011 and 2023

tate where an individual decides to move during the winter months and whether individuals exhibit interannual fidelity to overwintering areas or if animal location varies annually.

From late winter (i.e. March) through mid-spring (i.e. May), common thresher sharks that overwinter in continental shelf waters of the southeastern USA begin to move north along the coast and converge with sharks that have moved westward from off-shelf waters, yielding a core UD from Cape Hatteras north to southern New Jersey. Curiously, 2 individuals that were tagged in Canadian waters off the Scotian Shelf and Grand Banks of Newfoundland in September and October (a juvenile female and adult male, respectively) remained in off-shelf waters during the spring; the adult male never moved west of 52° W longitude from October through April and the juvenile female occupied shelf waters off Vir-

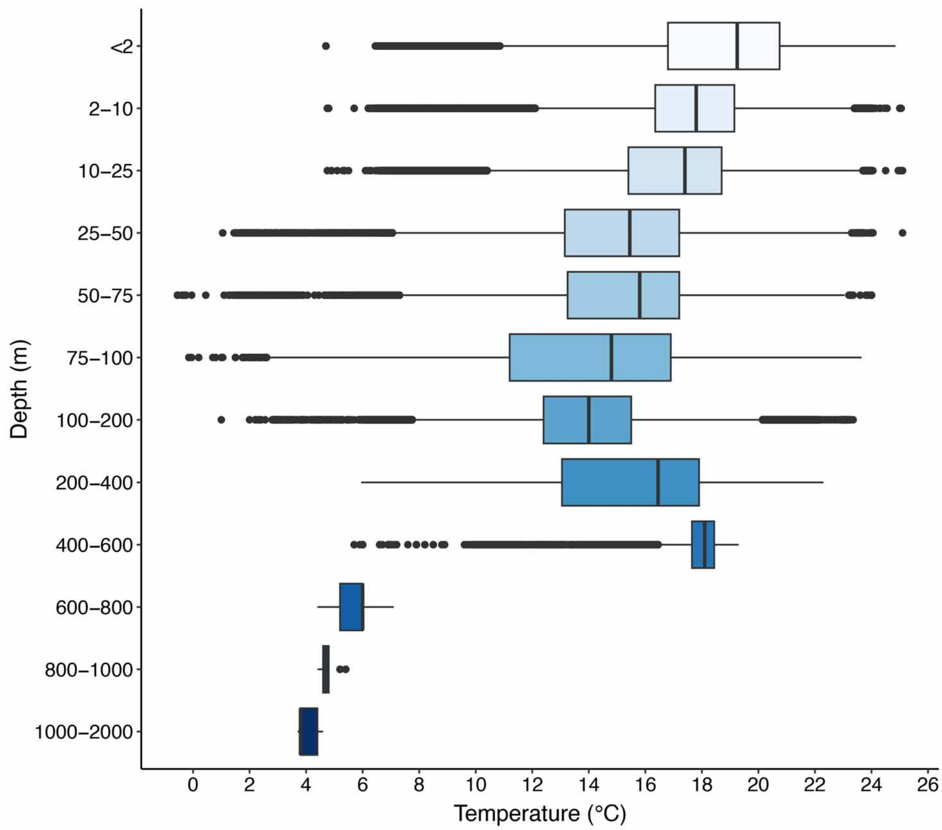

Fig. 7. Boxplot of temperature experienced by 33 tagged common thresher sharks (152–259 cm fork length) by depth. Upper and lower limits of each box: 25^{th} and 75^{th} percentiles; vertical black line: median; whiskers that extend beyond each box: 1.5× IQR; black circles: values outside this range

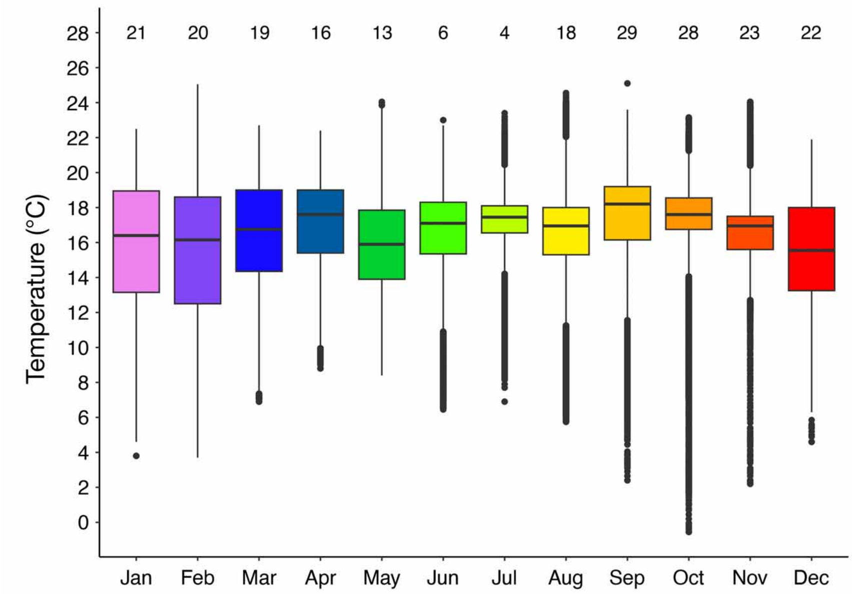

Fig. 8. Boxplot of temperature occupied by 33 common thresher sharks (152–259 cm fork length) across each month between 2011 and 2023. The numerals above the boxes indicate the number of individual sharks from which data were available in that month. Boxplot parameters as in Fig. 7

ginia and Maryland in December and January before moving eastward along the Gulf Stream from late January through early March. Thus, although most common thresher sharks that overwinter in off-shelf waters appear to move towards the US East Coast and commence northward migration in continental shelf waters in the spring, some individuals may simultaneously move north and east, potentially in association with the Gulf Stream. The existence of such movements is supported by catch records documenting common thresher shark presence east of the Grand Banks of Newfoundland and along the southern edge of Georges Bank in May and June (Kneebone et al. 2020), which are areas unlikely to be reached in spring by sharks that migrated along the coast.

The distribution of PSAT-tagged sharks during the summer and fall was primarily focused within continental shelf waters and closely matched trends evident in fisheries-dependent catch records described in Kneebone et al. (2020). During summer, the core UD of geolocated sharks occurred in continental shelf waters from New Jersey to Cape Cod, with a lower likelihood UD extending into the Gulf of Maine and along bathymetric shelf break waters on the southern edge of Georges Bank and the Scotian Shelf. Although UDs of geolocated sharks demonstrated limited use of the western Gulf of Maine during the summer and fall, the species regularly occurs in this area during these seasons, as evidenced by the existence of numerous fisheries-dependent catch records (Kneebone et al. 2020), PSAT tag deployments in this study (Fig. 1B), and the author's own observations (J. Kneebone pers. obs.). This fine-scale discordance in the degree of near-coast habitat use may stem, in part, from potential mismatches in nearshore depth–temperature conditions present in the 3D ocean model used to generate the OHC likelihood for geolocation, which can lead to an off-shelf bias in the resulting UDs and tracks (Nielsen et al. 2023, Arostegui et al. 2024b). In fall, many common thresher sharks begin to move southward along the US East Coast, traveling through coastal waters of the Mid-Atlantic Bight (New York to Virginia), with some returning to overwintering grounds off the southeastern USA. By contrast, other individuals continue to move eastward into Canadian waters along the Scotian Shelf and Grand Banks of Newfoundland in the fall, where some remained through winter and others remained only briefly before migrating westward towards the US East Coast.

Seasonal horizontal movements of common thresher sharks in the WNA were more well-defined and spatially expansive than what has been described for the species off the west coast of North America in the EPO. In the WNA, both juvenile and adult common thresher sharks exhibited seasonal migrations throughout continental shelf and off-shelf waters that spanned nearly 20 degrees of latitude (from ~27° to 47° N) and over 40 degrees of longitude (from ~80° to 40° W), with complete emigration from northerly and southerly latitudes during the winter and summer months, respectively. By contrast, common thresher sharks in the EPO are thought to undergo partial migration, wherein some individuals, especially young juveniles, remain within more localized regions throughout the year (e.g. the southern California Bight; Cartamil et al. 2016), while larger sharks undergo more extensive movements out of core habitat during the spring and winter (Kinney et al. 2020). Notably, inshore–offshore movements were also described in a single adult common thresher shark tracked off southern Australia (Heard et al. 2018). In the EPO, movements of tagged juvenile common thresher sharks (<120 cm FL) have also been shown to primarily occur in continental shelf waters, while fishery catch records suggest that adults are distributed further offshore (Cartamil et al. 2016). Although juvenile common thresher sharks measuring <120 cm FL were not tagged in this study, catches of individuals measuring <100 cm FL were largely restricted to continental shelf waters along the east coast of the USA (Kneebone et al. 2020), a trend that is more comparable to what is evident in the EPO. Additional research is required to describe the movement patterns of young juvenile common thresher sharks in the WNA.

Tagging data showed no evidence of size- or sex-linked movements in the WNA, with both juveniles and adults and males and females occurring over similar geographic areas and exhibiting similar horizontal movement patterns throughout the year. This finding is consistent with trends in seasonal distribution evident in fisheries-dependent data (Kneebone et al. 2020), and suggests that common thresher sharks do not segregate by sex and may not migrate in accordance with their reproductive status, a scenario present in other shark species (e.g. sand tiger *Carcharias taurus*, Bansemer & Bennett 2011; school shark *Galeorhinus galeus*, McMillan et al. 2019). However, long-term tracking data were available from only 4 adult female common thresher sharks, which may be most likely to engage in different horizontal movements associated with gestation and parturition (Anderson et al. 2025). In the EPO, both size and sex were found to be correlated with common thresher shark horizontal movements, with larger individuals and females being more likely to move out of core habitat in the southern California Bight (Kinney et al. 2020). However, individuals monitored in the EPO (range: 76–200 cm FL, 114 ± 30 cm FL) were mostly smaller than the sharks that were tracked in the WNA (range: 122–259 cm FL, 181 ± 32 cm FL) and included young juveniles that were tagged on nursery grounds (Cartamil et al. 2016). Thus, the effect of body size on horizontal movements reported in the EPO by Kinney et al. (2020) may be representative of the ontogenetic changes that occur early in life, but may not necessarily be indicative of behaviors exhibited by larger, mature common thresher sharks in EPO.

4.2. Vertical movements and habitat use

Over all tracking days, tagged common thresher sharks spent the majority (~87%) of time in depths <50 m, but occurrence in these shallower depths was more prevalent when sharks were assumed to be occupying continental shelf waters (i.e. tracking days when the maximum depth was <200 m). When present in off-shelf waters (i.e. tracking days when the maximum depth was >200 m), tagged sharks spent only ~30% of the time in waters <50 m and instead penetrated deeper epi- and mesopelagic depths, spending the greatest amount (~52%) of time in depths between 100 and 400 m. This differential use of the water column across on- and off-shelf habitats may be related to foraging and prey distribution. For example, the occupancy of mesopelagic depths when off-shelf may be associated with foraging for cephalopods, particularly squid, which are a major component of the common thresher shark's diet (Cortés 1999). Similarly, while present on the continental shelf, the frequent use of depths from the surface to 50 m may be associated with foraging for schooling fishes, including Atlantic menhaden *Brevoortia tyrannus*, Atlantic saury *Scomberesox saurus*, bluefish *Pomatomus saltatrix*, or sand lance *Ammodytes* spp., which are among the common thresher shark's primary prey species off the northeastern USA (M. Passerotti, pers. comm.). Of note, sand lance were the dominant species evident in over 600 common thresher sharks sampled in the WNA (M. Passerotti pers. comm.), which, together with the occurrence of other benthic fishes (e.g. hakes, flounders, and skates) in the diet, supports our assumption that common thresher sharks regularly visit the benthos when occupying waters on the continental shelf.

Common thresher sharks tracked in the WNA dove to deeper depths than has been recorded for the species in the EPO (560 m; Cartamil et al. 2016) and off southern and eastern Australia (144 m, Heard et al. 2018; 640 m Stevens et al. 2010, respectively), but occupied meso- and bathypelagic habitats less frequently than the pelagic thresher *A. pelagicus* and bigeye thresher. The shallower dive depths recorded for common thresher sharks in the EPO and off Australia may be due to the existence of physiologically limiting oceanographic conditions in these regions (e.g. colder temperatures and lower dissolved oxygen at mesopelagic depths; Prince & Goodyear 2006) or perhaps the limited number of individuals that were tracked in these regions (n = 6). However, the consistent use of shallow depths in the EPO (<20 m; Cartamil et al. 2011) and WNA (70% of time spent in depths <25 m) indicates that the common thresher shark primarily resides in the well-mixed surface waters throughout its global range. The primary occurrence of common thresher sharks in shallow, epipelagic depths contrasts with both the pelagic thresher and bigeye thresher, which occupy mesopelagic depths with much greater regularity (Weng & Block 2004, Coelho et al. 2015, Arostegui et al. 2020, Shidqi et al. 2024), and may be related to unique morphological specializations (e.g. large gill surface area that may increase oxygen uptake in hypoxic waters; Wootton et al. 2015).

Tagged common thresher sharks occupied a broad temperature range (from −0.5 to 25.6°C) in the WNA but spent over 97% of the time between 10 and 22°C, consistent with trends in fisheries-dependent data that documented the majority (78%) of catches occurring in SSTs of this same range (Kneebone et al. 2020). This selected temperature range was broader, albeit inclusive of selected temperatures reported in the EPO (14−17°C; Cartamil et al. 2016) and western Pacific off New Zealand (18−20°C; Cao et al. 2011). PSAT tag data from this study also recorded the coldest water temperatures reported for common thresher sharks throughout their global range. However, it should be noted that tracked sharks cumulatively spent <1% of their time in temperatures colder than 8°C, indicating that although the penetration of cold waters is possible, extended occupancy does not occur even with the species' regional endothermic capabilities (Eschricht & Müller 1835, Bernal & Sepulveda 2005, Patterson et al. 2011). With respect to thermal maxima, while a single common thresher shark tagged off the east coast of Australia was recorded in water temperatures as high as 27°C (Stevens et al. 2010), individuals tracked by this study in the WNA cumulatively spent <0.5% of the time in temperatures >22°C, which may be the upper end of long-term thermal tolerance in this species.

In this study, we did not investigate the potential biotic and oceanographic drivers of common thresher shark seasonal migration in the WNA; however, the primary occupation of a relatively defined temperature range by tagged individuals throughout the year (i.e. 14−20°C; Figs. 4, 5, & 8) provides some evidence that the species migrates seasonally to remain at specific temperatures or to seek prey that inhabit this temperature range. Off the west coast of the USA, seasonal common thresher shark movements were found to be more associated with extrinsic oceanographic factors (e.g. North Pacific Gyre Oscillation) than seasonal temperature fluctuation (Kinney et al. 2020). However, common thresher shark seasonal movements in the WNA were similar across years, suggesting that basin-scale extrinsic oceanographic factors (e.g. the North Atlantic Oscillation) may not be as influential as they are in the EPO. Nonetheless, additional analyses are required to better evaluate the suite of factors that drive migration in this species.

4.3. Management implications

The results of this study support, but do not necessarily confirm, the assumption made by ICES (2009) that common thresher sharks that inhabit the WNA constitute a distinct stock. Across over 8000 tracking days, there was no evidence of trans-Atlantic movements in common thresher sharks tagged in WNA, including among individuals tagged in Canadian waters along the Scotian Shelf and Grand Banks of Newfoundland out to ~50° W longitude and those individuals tracked for periods of 270 d (9 mo). Notably, the eastern extent of common thresher shark movements in the WNA was similar to those described for shortfin mako *Isurus oxyrinchus* tracked with satellite tags for periods up to 527 d (Vaudo et al. 2017), a species that has been confirmed to make trans-Atlantic movements through extensive conventional tag data (Kohler & Turner 2019). In the WNA, there is an extreme paucity of long-term fishery-dependent recapture records for the common thresher shark (n = 2; Kohler & Turner 2019); thus, it is possible that longer-term tracking may reveal broader-scale movements throughout the North Atlantic basin.

Areas designated as common thresher shark EFH under the US Magnuson-Stevens Fishery Conservation and Management Act should be expanded based on horizontal movement and residency patterns revealed by PSAT tags. Currently, NOAA Fisheries EFH designation for common thresher shark includes most continental shelf waters from the Gulf of Maine and Georges Bank south to Cape Lookout, North Carolina (NMFS 2017), but does not include any of the overwintering areas identified by this study off the southeastern USA (South Carolina to northeastern Florida) or Slope Sea waters within the US exclusive economic zone (EEZ). Given the protracted occupation of overwintering grounds (i.e. 3−4 mo) by both juvenile and adult common thresher sharks, it stands to reason that EFH should be expanded to include these areas and ensure that they are given consideration as important habitat for the species.

The extensive use of the US EEZ by common thresher sharks suggests that the assessment and management of the species may best be achieved at the domestic level or in a partnership between the USA and Canada. In US waters of the Atlantic, common thresher sharks are managed by the NOAA Fisheries Highly Migratory Species Management Division, which manages fishery removals through recreational minimum size retention limits and domestic harvest quotas. Since 1999, common thresher shark landings have been managed as part of a 'pelagic shark' complex that includes an annual quota of 488 t for landings of common thresher shark, shortfin mako, and oceanic whitetip *Carcharhinus longimanus* in the EEZ (US Office of the Federal Register 1999). However, due to conservation actions in 2022 (US Office of the Federal Register 2022) and 2024 (US Office of the Federal Register 2024), the common thresher shark is currently the only one of the 3 species whose harvest remains permissible by law, thereby potentially subjecting the species to higher levels of fishing mortality than was originally intended. Given the regular occurrence of common thresher shark in US commercial and recreational fisheries (Young et al. 2016), the reliance upon US waters across all life stages (Kneebone et al. 2020, this study), and the evidence suggesting a distinct WNA stock, regulators should consider managing the species akin to a coastal shark species that is mostly restricted to domestic waters (e.g. sandbar shark *Carcharhinus plumbeus*; SEDAR 2017) rather than one that regularly traverses international boundaries (e.g. blue shark *Prionace glauca*).

4.4. Tag performance

The PSAT tags deployed by this study provided extensive data that improved the understanding of common thresher shark ecology in the WNA, but tag malfunctions reduced scientific opportunity, data recovery, and increased error associated with geolocation tracks. Of the 39 miniPAT tags deployed, 12 (31%) experienced a hardware failure in the form of a nosecone pin break (n = 8; Lam et al. 2020) or malfunctioning pressure (depth) sensor (n = 4), which led to premature release of the tag in most cases well short of the programmed (270 d) deployment period (Table 1). One tag also reported only a small portion of data due to a failure of the battery after completing a 270 d deployment. In addition, 7 of the 32 reporting miniPAT tags (22%) experienced a firmware issue wherein light data were only collected for a portion of the track. The lack of light data (the primary input traditionally used for PSAT geolocation; Nielsen et al. 2006) not only precluded the estimation of (light-based) latitude and longitude for portions of the track but also increased geolocation error due to the reliance on only depth and temperature (i.e. SST and OHC) likelihood layers in the hidden Markov model for geolocation during periods when no light locations were available. Taken together with tag non-reporting rates (miniPAT: 18%; mrPAT: 14%), nearly half (48%) of the PSAT tags deployed by this study yielded limited or no data. Given the scientific value of PSAT tags for informing population assessment and management (Sippel et al. 2015), tag manufacturers should continue to make strides to improve PSAT technology and communicate known issues to tag users to ensure maximum data return and the reduction in geolocation uncertainty. Nonetheless, despite the performance issues experienced in this study, our results and those of other studies (e.g. Gatti et al. 2020, Arostegui et al. 2024a) demonstrate the continued potential of PSAT tags to yield detailed ecological and management-relevant insight into the movements and habitat use of marine animals over protracted tracking periods.

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Appendix.

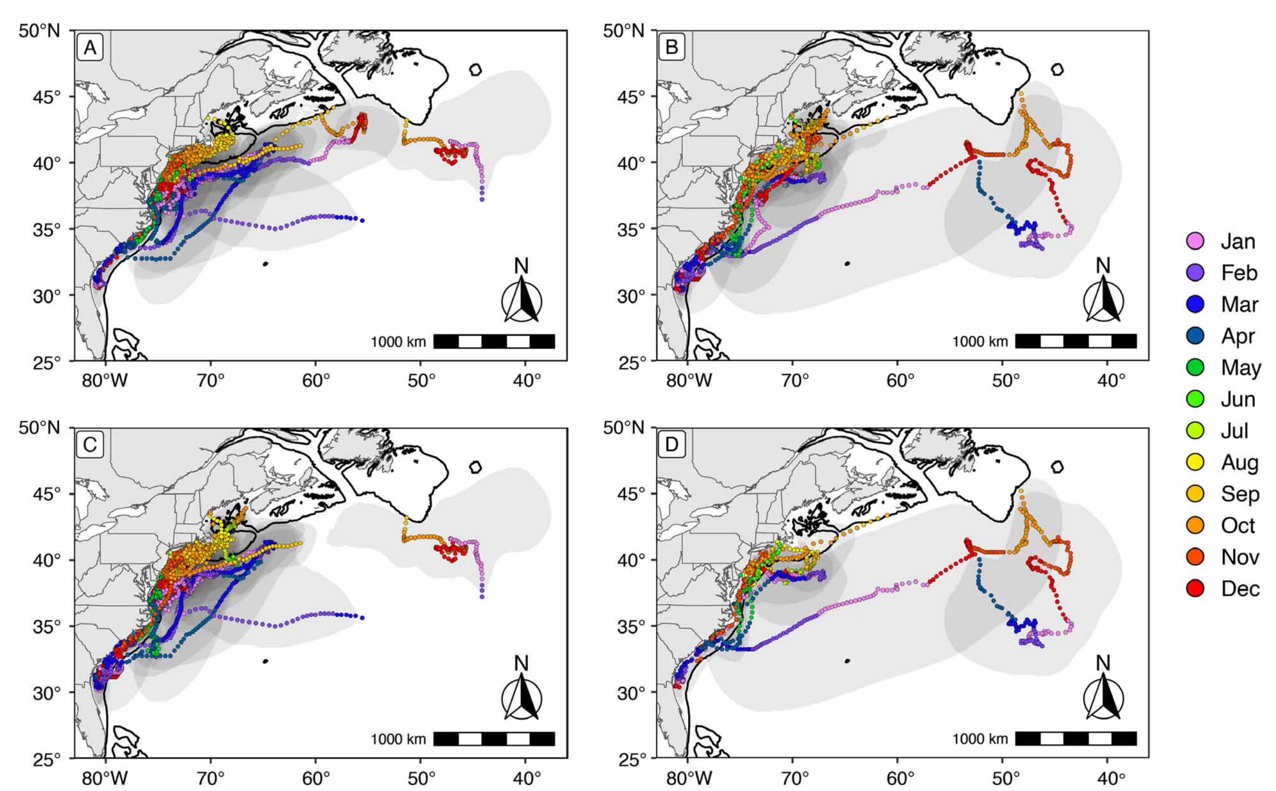

Fig. A1. Most probable geolocation tracks generated for (A) juvenile (n = 21 individuals), (B) adult (n = 11 individuals), (C) female (n = 20 individuals), and (D) male (n = 8 individuals) common thresher sharks tagged from 2011 to 2023. Colored circles: daily estimated positions by month; light grey shaded area: 95% utilization distribution associated with each shark; solid black line: 200 m isobath

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