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THEMED ISSUE: TELEMETRY NETWORKS IN THE NORTHWEST ATLANTIC AND CARIBBEAN

Seasonal Presence of Atlantic Sturgeon and Sharks at Cape Hatteras, a Large Continental Shelf Constriction to Coastal Migration

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Abstract
Cape Hatteras is a major topographic feature on the continental shelf of the U.S. eastern seaboard that changes the dynamics of nearshore large ocean currents, including the Labrador Current and Gulf Stream. Cape Hatteras constricts shelf habitat and restricts the migratory corridors of highly migratory species through this area. Our objective was to describe the seasonal patterns of presence for three species—the Spiny Dogfish *Squalus acanthias*, Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus*, and Sandbar Shark *Carcharhinus plumbeus*—and analyze environmental conditions associated with fish presence near this feature. These species are managed under the Magnuson–Stevens Act, and two of them are also listed as species of concern under the Endangered Species Act. Transmitter detections from tagged fish recorded by the Cape Hatteras acoustic array, which was deployed just south of the cape, indicated that these species are present year-round. The greatest number of detections occurred from November through April. This simple baseline of seasonal presence can provide insights for regional offshore development activities, which have the potential to affect movement patterns of migratory species through the Cape Hatteras constriction. Our results show the value of strategically placed acoustic arrays for observing fish habitat use and provide presence/absence data to enhance our understanding of species ecology and distribution.

Many large, migratory fish and marine mammal species inhabit U.S. continental shelf waters along the East Coast and exhibit long-distance seasonal migrations between northern and southern shelf habitats. However, Cape Hatteras, located on the Outer Banks of North Carolina, USA, forms a natural bottleneck—only 30 km wide—that is caused by narrowing of the coastal shelf in this region (Townsend et al. 2004). Oceanographic patterns in the area may also contribute to this bottleneck. The outflow of Chesapeake Bay waters along the shelf inshore margin combines with the southward-flowing, cold Labrador Current to collide with the warm Gulf Stream, which flows northward. Cape Hatteras is the collision point for these two currents, resulting a large shift in water temperatures within the area and a shunting of these currents toward the outer continental shelf and eventually to the open northwest Atlantic Ocean (e.g., see Townsend et al. 2004). Therefore, Cape Hatteras serves as the dividing line between two major ecoregions: the Virginian (northern) and the Carolinian (southern). The shelf distributions of smaller temperate and semi-tropical fish species are often limited by this thermal regime shift, but migratory fish species often proceed through this dynamic area during seasonal migrations (Hayden et al. 1984; Fautin et al. 2010). These animals, in adhering to preferred current or temperature clines, may be effectively channeled into narrow warmwater and coldwater corridors along the continental shelf. Thus, the combination of physical factors and unique oceanographic conditions establishes a relatively high-energy, dynamic region that effectively funnels migratory fish through a smaller area, where they can be studied efficiently using acoustic telemetry.

The use of acoustic receiver gates and arrays to study the migration patterns of marine fish moving through open-ocean habitats has become more practical with the development of regional and international data sharing networks, such as the Ocean Tracking Network (O'Dor and Stokesbury 2009), the Atlantic Cooperative Telemetry (ACT) Network (http://theactnetwork.com/; Fox et al. 2009; Young et al. 2020, this themed issue), regional integrated ocean observing systems (e.g., Gulf of Maine Ocean Observing System), and the Pacific Ocean Shelf Tracking Project (Jackson 2011). In addition, acoustic arrays have been deployed to study localized movement patterns and may be useful in assessing community-level responses to anthropogenic activities (Boehlert and Gill 2010; Wyman et al. 2018). For example, in a comprehensive report intended to summarize potential impacts to fisheries resources in coastal areas of southern New England, the Bureau of Ocean Energy Management (BOEM) noted the need for robust baseline information collected through surveys conducted with fisheries gear (Petruny-Parker et al. 2015). However, equally important was the collection of fisheries-independent data combining the deployment of fisheries gear with, among other things, acoustic telemetry, biological (fisheries-independent) surveys, and oceanographic modeling (Petruny-Parker et al. 2015). The need for this type of research has also been noted in papers published on best practices for evaluating the environmental impacts of such infrastructure development based on lessons learned from an assessment of European wind farms (e.g., Bailey et al. 2014). Alternative energy development in U.S. offshore environments is projected to increase rapidly in the coming decade (Luthi 2017); therefore, a strong, multi-pronged approach to biological research is needed in order to provide the information for science-based decisions regarding development strategies along the U.S. coasts.

Herein, we describe detection data from a strategically placed acoustic array at Cape Hatteras (hereafter, "Hatteras array") to provide baseline information about highly migratory species utilizing this constricted and dynamic corridor. Originally, the Hatteras array was developed and deployed in 2008 to address commercial fishing issues related to the highly migratory Spiny Dogfish *Squalus acanthias*; the area between Cape Hatteras and Cape Lookout to the south seemed to be the overwintering grounds for a large portion of the western Atlantic migratory stock (Rulifson and Moore 2009). Other studies on Spiny Dogfish have also revealed their consistent occurrence near Cape Hatteras (Cudney 2015), while detections of Spiny Dogfish on arrays managed by ACT Network collaborators farther north have documented the species' extensive migratory behavior (Rulifson et al. 2013). However, shortly after the initial array deployment we discovered that several highly migratory fish species tagged with acoustic transmitters by other coastal investigators were detected on the Hatteras array. The information obtained by the Hatteras array is consistent with research needs identified by the BOEM on large, migratory species; the BOEM Kitty Hawk Wind Energy Area (49,535.5 ha [122,405 acres]) is about 44 km from shore and extends southeast for about 48 km, placing the wind energy area just north of the Cape Hatteras narrowing. In addition, offshore sand mining is in progress in this area, and exploration for oil and gas is expected. The BOEM has specifically noted (1) the need for conducting both hydroacoustic and acoustic telemetry surveys in assessing the seasonal distribution of Endangered Species Act-protected Atlantic Sturgeon within and around proposed wind energy areas for at least 3 years prior to construction; and (2) the need to use acoustic telemetry to assess associations, redistribution, and migratory patterns of mobile fish and invertebrates around wind energy sites (Petruny-Parker et al. 2015). The purpose of the present study was to document seasonal presence of three highly migratory fish species—the Spiny Dogfish, Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus*, and Sandbar Shark *Carcharhinus plumbeus*—in the physical constriction caused by Cape Hatteras. This information, coupled with the use of ocean buoy sensors to determine the correlations of environmental data associated with these species, can be used to fill in data gaps on habitat associations for some migratory species in Hatteras Bight. Results of our research provide baseline data about species presence prior to major new anthropogenic activity in this region.

STUDY SITE

The study site encompasses coastal regions surrounding Cape Hatteras, North Carolina (Figure 1). The array site was located within the Hatteras Bight of Raleigh Bay, a coastal embayment that is bordered by Diamond Shoals (Cape Hatteras) to the north and Lookout Shoals (Cape Lookout) to the south. The continental shelf narrows from roughly 100 km to less than 50 km around Cape Hatteras (Werner et al. 2001). The Gulf Stream is often positioned between the 40- and 70-m isobaths (Werner et al. 2001) and follows the edge of the continental shelf until it reaches Cape Hatteras, where it is deflected offshore. Farther inshore, the Labrador Current moves southward tightly along the North American coast. This wedge of colder, fresher water can force the western edge of the Gulf Stream away from the coastline during winter months (Schollaert et al. 2004). This confluence of high-energy currents—and their associated gyres and eddies—can generate upwellings that enhance primary productivity in the region (Lohrenz et al. 2002). Upwellings in the area are also often driven by wind events (Wells and Gray 1960) and local topography (Blanton et al. 1981).

METHODS

Array deployment.— A Vemco VR2W acoustic receiver array (Vemco, Bedford, Nova Scotia) was deployed to track Spiny Dogfish movements in the Hatteras Bight but later supported research on a variety of sharks, Atlantic Sturgeon, Striped Bass *Morone saxatilis*, and other species. Twelve receivers were deployed between November 2008 and April 2009. The first receiver was situated 750 m from the beach to avoid swash zone conditions, and the subsequent 11 receivers in the array were spaced 600–1,000 m apart based on range testing within the nearshore environment, which will be addressed in a separate paper (Figure 1). From December 2009 to July 2010 and from December 2010 to November 2011, 10 VR2W receivers were deployed approximately 1,600 m apart along the same line in order to span a greater cross-section of the Hatteras Bight (consistent with research objectives). The Hatteras array was next deployed from November 1, 2012, through April 21, 2014, using similar spacing between receivers. Receivers were checked and detection data were downloaded every 2–6 months, weather permitting.

The Hatteras array was deployed between the National Oceanic and Atmospheric Administration (NOAA) weather station at Cape Hatteras Coast Guard Station (station HCGN) and the Diamond Shoals NOAA weather buoy (station 41025; Figure 1). Daily mean weather

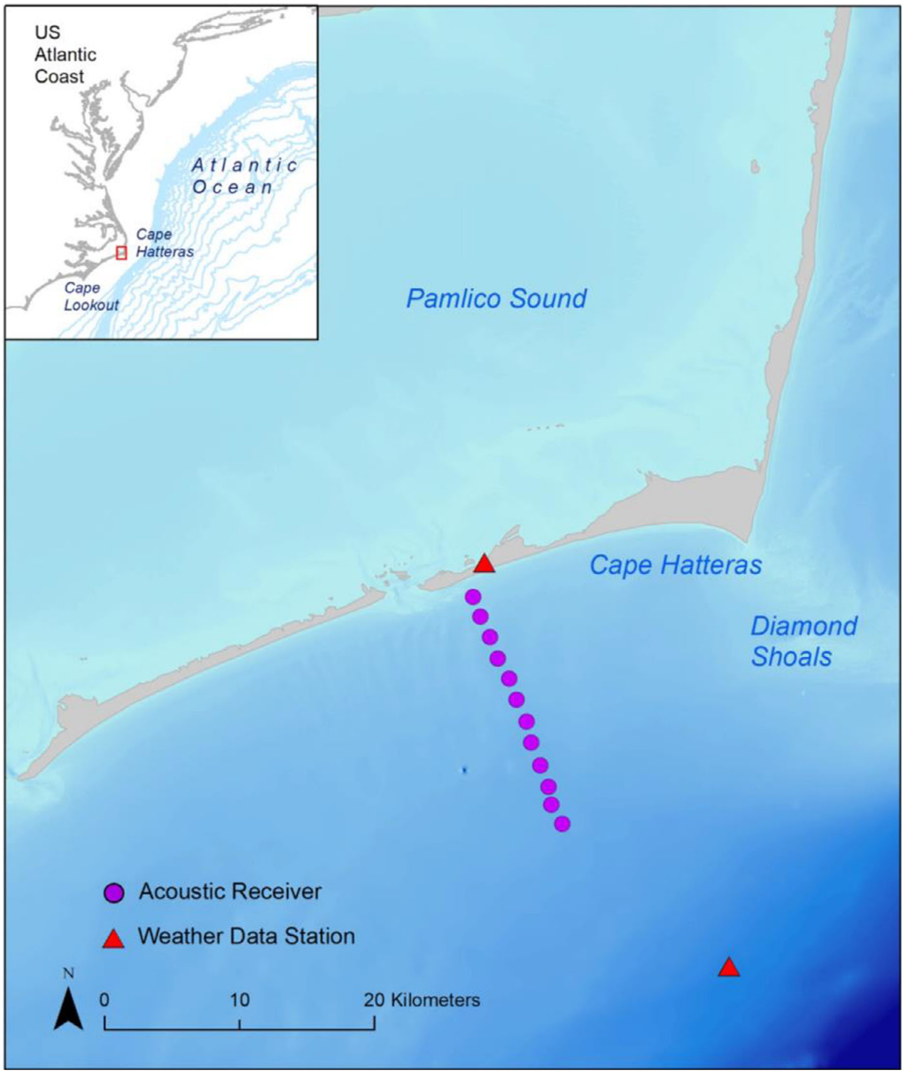

FIGURE 1. Locations of acoustic receiver deployment sites in the Cape Hatteras, North Carolina, array and National Oceanic and Atmospheric Administration weather stations supplying environmental data.

variables recorded by the NOAA data buoys at these two locations were acquired from the National Data Buoy Center (www.ndbc.noaa.gov) to assess the correlation of environmental variables with the observed patterns of tag detection. Environmental variables used in this analysis were wind direction (radians), wind speed (m/s), air temperature (°C), and sea surface temperature (SST; °C). The average daily measurements between the two data buoys were used in order to avoid bias toward offshore or inshore conditions and to cover gaps in measurements when one of the buoys was nonoperational.

Deployment schematics varied by year, largely in response to modifications made to improve the speed and ease of deployment and to create a more durable equipment package that could withstand the harsh weather and sea conditions off coastal North Carolina. The final version of the anchor system consisted of both a 45-kg concrete block and a 5.8-kg Danforth anchor, to which was attached a VR2W bridle made of 408-kg-test monofilament (to reduce reception interference), stainless-steel cable, and a hard trawl float (Figure 2). The deployment site was marked with a large crab pot float or poly ball and radar reflector attached to a polypropylene float line (which included a marine mammal breakaway, consistent with gear requirements for the local trap fisheries) connected to the subsurface receiver and anchoring system. Details of the various configurations were described by Cudney (2015).

Despite regular maintenance, this area proved challenging for acoustic array deployment. In the first 2 years of the research program, three receivers were moved offsite (likely due to encounters with fishing vessels) and were

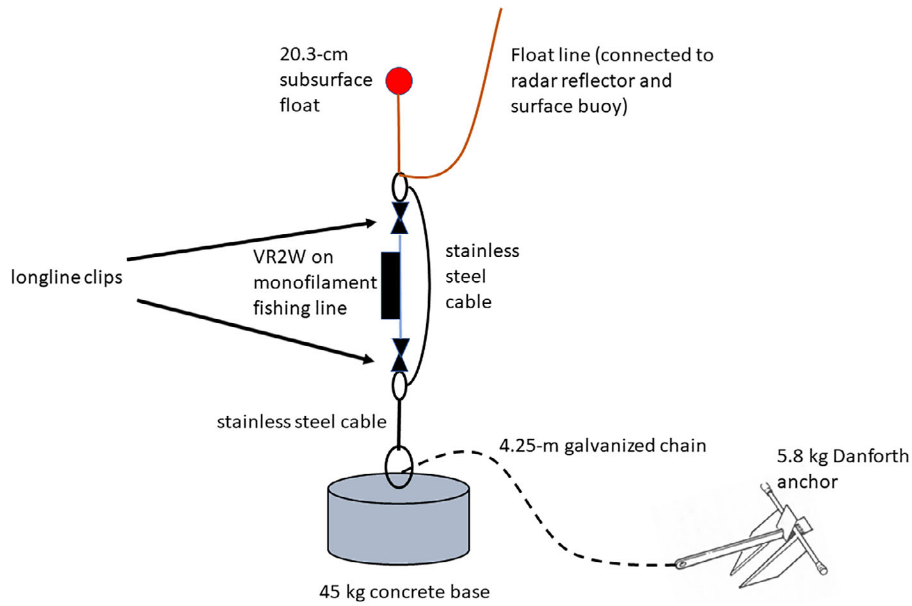

FIGURE 2. Final design configurations for the anchor system and Vemco VR2W mount.

never relocated (Cudney 2015). In 2011, Hurricane Irene significantly affected the receiver array. All receivers were pushed offsite approximately 3,200 m to the northeast. Additionally, the array was severely damaged by a series of nor'easters during the winter of 2013–2014, and only 4 of the original 12 receivers were recovered at the end of the 2012–2014 study (Cudney 2015).

Data analysis.— Species were tagged (as described by Cudney 2015; Dell'Apa et al. 2017; Melnychuk et al. 2017; Hager 2019) by researchers who are members of the ACT Network, which hosts a database of acoustic transmitters deployed by researchers from Nova Scotia to Georgia. The ACT Network database was used to identify all transmitter identification codes and to contact the researchers who originally deployed the transmitters. Permission to use the detection information associated with each transmitter was granted by the responsible researchers for all tag detections analyzed in this study.

The species analyzed included the Atlantic Sturgeon, Spiny Dogfish, and Sandbar Shark. Because differences in the timing of receiver deployment would likely affect the detection probability of tagged animals, the tag detection analyses from the 2008–2011 and 2012–2014 deployments were conducted separately. During 2008–2011, receivers were deployed from fall to spring only, whereas for 2012–2014 they were deployed year-round. To identify seasonal and year-round patterns in species presence at the Hatteras array, the daily presence or absence for each species within the array was calculated and used in the modeling analysis.

Generalized linear models (GLMs) were used to identify potential relationships with other species or environmental factors influencing patterns of tag detection by the Hatteras array. For each species, GLMs were run with daily presence as the dependent variable and daily mean environmental measurements (wind direction, wind speed, air temperature, and SST) and numerical day of year as independent variables. Because presence data are inherently binomial and initial histogram analysis found our data to be zero-inflated, GLMs using three different distributions were tested: binomial, negative binomial, and zero-inflated negative binomial. The model distribution with the lowest corrected Akaike's information criterion (AIC_c) value was chosen to predict the number of individuals in the area of the Hatteras array based on significant environmental or temporal variables. All analyses were conducted using R (R Core Team 2018), and zero-inflated models were run using scripts from the package *pscl* (Zeileis et al. 2008).

RESULTS

Spiny Dogfish were detected by the Hatteras array during the 2008–2011 deployment; tags for this species expired prior to 2012. Atlantic Sturgeon were detected during both the 2008–2011 and 2012–2014 deployments, and Sandbar Sharks were detected during the 2012–2014 deployment (Table 1). Best-fitting models of target species presence indicated a non-zero-inflated binomial distribution for all species (Table 2).

Initial plots of the number of individuals detected against day of year revealed some consistent detections of all three species during winter for both deployments (Figure 3). Year-round deployment of the acoustic array during the 2012–2014 deployment allowed for detections of

TABLE 1. Total number of individual transmitters and tag detections for focal species detected on the Cape Hatteras acoustic array during the 2008–2011 and 2012–2014 receiver deployments.

Species, deployment period	*n* detections	*n* individuals
Spiny Dogfish, 2008–2011	7,394	43
Atlantic Sturgeon, 2008–2011	653	24
Atlantic Sturgeon, 2012–2014	854	67
Sandbar Shark, 2012–2014	37	8

TABLE 2. Best-fitting distribution, corrected Akaike's information criterion (AIC_c), and degrees of freedom (df) for generalized linear models that were used to assess environmental relationships with the number of individual Spiny Dogfish, Atlantic Sturgeon, and Sandbar Shark transmitters detected on the Cape Hatteras array during the 2008–2011 and 2012–2014 deployments.

Species, deployment period	Best-fitting model distribution	AIC_c	df
Spiny Dogfish, 2008–2011	Binomial	332.97	13
Atlantic Sturgeon, 2008–2011	Binomial	186.11	6
Atlantic Sturgeon, 2012–2014	Binomial	382.38	12
Sandbar Shark, 2012–2014	Binomial	116.83	12

tagged animals later in late winter/early spring and earlier in late fall/early winter than were recorded during the 2008–2011 deployment.

Spiny Dogfish

In total, 7,394 detections of 43 tagged Spiny Dogfish recorded by the array during 2009–2011 were included in this analysis (Table 1). Detection events for Spiny Dogfish ranged from less than 1 min in duration to over 24 h. In the best-fitting GLM for Spiny Dogfish, air temperature, SST, and day of the year were significantly related to presence likelihood (Table 3). Increased presence likelihood of Spiny Dogfish was associated with SSTs and air temperatures less than 23°C and appeared to peak at temperatures below 10°C (Figure 4). Predicted numbers of Spiny Dogfish were considerably greater during the late winter and early spring than during the early winter (Figure 5).

Atlantic Sturgeon

Atlantic Sturgeon records included 653 detections of 24 individuals during the 2008–2011 deployment and 854 detections of 67 individuals during the 2012–2014 deployment (Table 1). Atlantic Sturgeon that were detected during the 2008–2011 deployment were originally tagged in tributaries of the Chesapeake Bay (65% of individuals), the Connecticut River (30%), South Carolina (5%), and Albemarle Sound, North Carolina (10%). Atlantic Sturgeon that were detected during the 2012–2014 deployment were originally tagged in the Hudson River (66% of individuals), tributaries of the Chesapeake Bay (15%), the Connecticut River (10%), Albemarle Sound (4%), South Carolina (3%), and the Delaware River estuary (1%).

The GLM results from 2008–2011 detections showed that air temperature and day of year had significant relationships with presence likelihood. For the 2012–2014 deployment, the number of Atlantic Sturgeon detected was significantly related to SST and day of the year (Table 3). Presence likelihood of Atlantic Sturgeon for the 2008–2011 period decreased with increasing air temperature, and no sturgeon were predicted to occur at air temperatures greater than approximately 18°C. During the 2012–2014 deployment, the presence likelihood of Atlantic Sturgeon was higher at SSTs less than approximately 27°C (Figure 6). In both deployments, the greatest predicted numbers of Atlantic Sturgeon occurred during the winter, with some presence in the late fall and early spring, but greater numbers were predicted to occur during the early winter in the 2008–2011 deployment (Figure 5).

Sandbar Shark

There were 37 detections of 8 individual Sandbar Sharks during the 2012–2014 deployment (Table 1). The majority of tag detections occurred during late winter and early spring (February–March), with sporadic detections during late fall (Figure 3). Sandbar Shark presence did not show significant relationships with any of the environmental variables or with day of year (Table 3).

DISCUSSION

Detection data and GLMs indicated that Spiny Dogfish, Atlantic Sturgeon, and Sandbar Sharks likely use the Hatteras Bight as an overwintering habitat and migratory corridor and that all three species occur in this region within the same seasonal time frame. The highest numbers of transmitter detections and individuals for each species occurred during the mid- to late winter and early spring, with a lower peak during late fall and early winter. The results suggest that these species move around Cape Hatteras during their seasonal migrations between summer and winter habitats.

Spiny Dogfish

Analyses from this study and previous research (Cudney 2015) suggest that Spiny Dogfish utilize the Hatteras Bight area as part of their overwintering grounds. Migrations of many fish species along the mid-Atlantic are often responsive to tolerable isotherms (Able and Grothues 2007). Spiny Dogfish are no exception, and numerous studies between Maine and North Carolina have noted similar temperature associations. Results from this

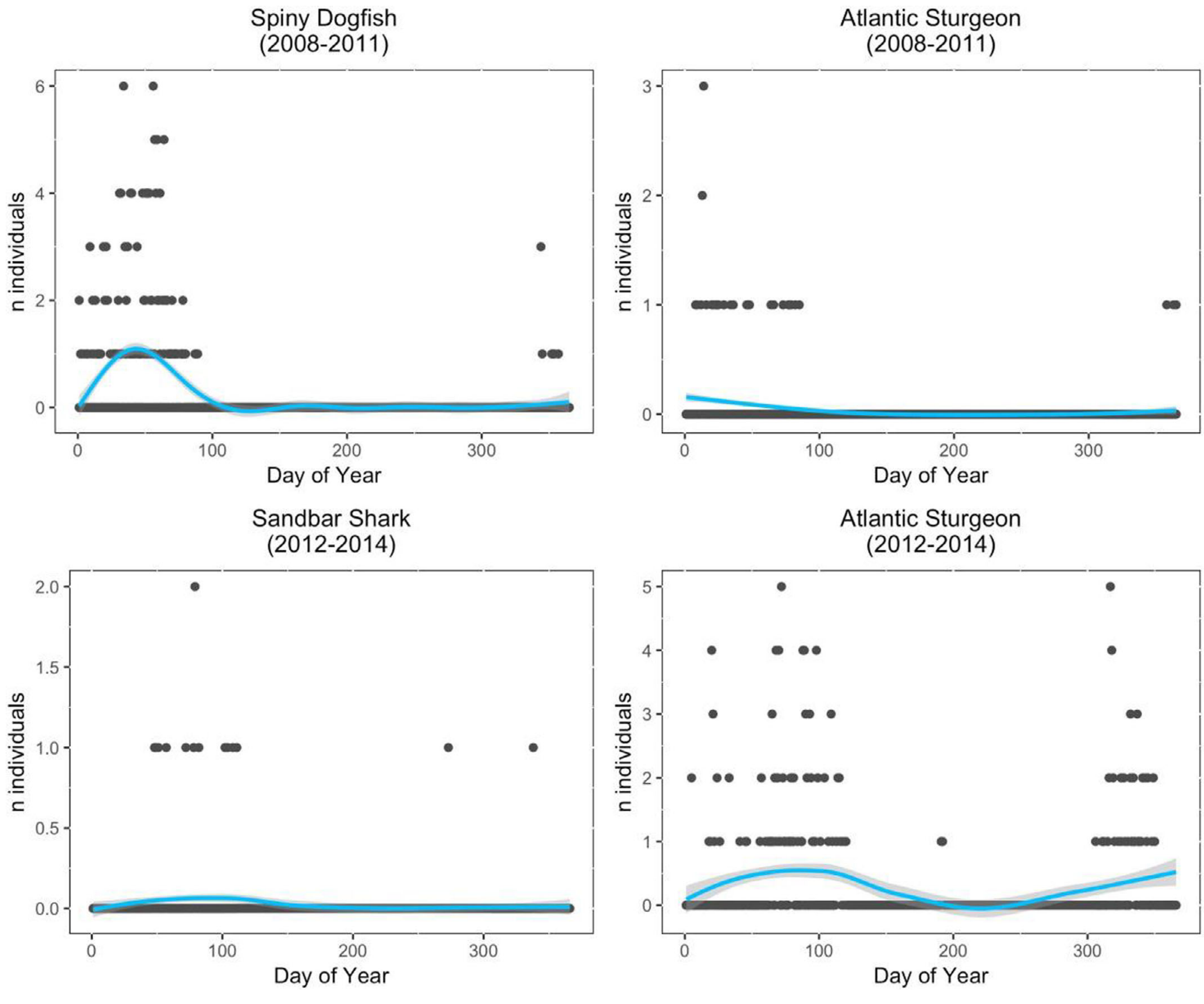

FIGURE 3. Number (n) of tagged individual Spiny Dogfish, Atlantic Sturgeon, and Sandbar Sharks detected by the Cape Hatteras array by day of year during the 2008–2011 and 2012–2014 deployments. Lines are smoothed trend lines (locally weighted scatterplot smoothing) showing SE.

analysis showed a preference for cooler temperatures in both air and water, with maximum presence likelihood at temperatures less than 10°C, which is consistent with the findings of other research on Spiny Dogfish temperature associations. Shepherd et al. (2002) noted strong associations of Spiny Dogfish with the 8°C (47°F) isotherm; however, they were commonly found associated with temperatures ranging from 6°C to 9°C (Shepherd et al. 2002). Sagarese et al. (2014) noted that the proportion of mature female Spiny Dogfish caught in federal trawl surveys was related to temperature in the Middle Atlantic Bight and suggested that oceanographic factors like water temperature could influence population-level trends in distribution and sexual segregation (i.e., sharks, particularly females, were associated with warmer water temperatures). Similarly, results by Dell'Apa et al. (2017), who used a predictive modeling approach for adult Spiny Dogfish caught in fishery-independent surveys conducted in U.S. Atlantic coastal waters, suggested the presence of sex-based differences in the species' distribution, with a higher abundance of adult females in warmer waters and more males predicted to occur in colder waters.

The timing of detection by the Hatteras array—and microhabitat selection in the array's vicinity—is often coincident with the availability of coldwater masses around Cape Hatteras. Cudney (2015) noted peaks in Spiny Dogfish detections when shallow-water temperatures were less than 12–13°C. Rulifson and Moore (2009)

TABLE 3. Results of binomial generalized linear models (regression estimate, SE, *z*-score, and *P*-value) of relationships between environmental variables and the presence of Spiny Dogfish, Atlantic Sturgeon, and Sandbar Sharks detected by the Cape Hatteras array during the 2008–2011 and 2012–2014 deployments (SST = sea surface temperature).

Variable	Estimate	SE	*z*	*P*
Spiny Dogfish, 2008–2011				
Wind speed	−0.112	0.059	−1.914	0.056
Air temperature	−0.119	0.037	−3.234	0.001
SST	−0.156	0.038	−4.085	<0.001
Day of year	−0.012	0.002	−6.794	<0.001
Atlantic Sturgeon, 2008–2011				
Wind direction	−0.002	0.002	−1.069	0.285
Wind speed	−0.134	0.087	−1.533	0.125
Air temperature	−0.191	0.058	−3.282	0.001
SST	−0.037	0.053	−0.701	0.483
Day of year	−0.005	0.002	−2.633	0.008
Atlantic Sturgeon, 2012–2014				
Wind direction	−0.001	0.001	−0.381	0.406
Wind speed	−0.06	0.051	−1.17	0.242
Air temperature	−0.025	0.042	−0.588	0.557
SST	−0.182	0.043	−4.265	<0.001
Day of year	0.002	0.001	2.125	0.034
Sandbar Shark, 2012–2014				
Wind direction	0.004	0.004	1.174	0.24
Wind speed	0.074	0.115	0.646	0.518
Air temperature	0.072	0.094	0.765	0.444
SST	−0.139	0.097	−1.439	0.15
Day of year	−0.006	0.003	−1.625	0.104

noted that six Spiny Dogfish aggregations with an estimated 1 million individuals were found south of Cape Hatteras in temperatures that ranged between 8.0°C and 15.7°C, well within the range associated with elevated presence likelihood in our analysis. In a study of microhabitat selection by Spiny Dogfish off North Carolina, Cudney (2015) also noted that detections of Spiny Dogfish along the Hatteras array may be linked to weather patterns, with cooler air temperatures and prevailing wind patterns influencing the location and spatial extent of coldwater masses.

Atlantic Sturgeon

The Hatteras array clearly indicates the seasonal timing and relative abundance of acoustically tagged Atlantic Sturgeon as well as the importance of the continental shelf restriction at Cape Hatteras to their movements. Based on both the timing of detection and environmental associations, Atlantic Sturgeon presence in the vicinity of Cape Hatteras started in late fall and continued throughout the winter and into spring. This trend was consistent during both the 2008–2011 and 2012–2104 deployment periods despite the fact that receivers were only deployed for part of the year during the 2008–2011 deployment. Therefore, results of the analyses for both deployment periods can be considered in aggregate for the purposes of predicting the timing of Atlantic Sturgeon presence in the Hatteras Bight. Although we do not have data on the directionality of movement, we do know the origin of the tagged Atlantic Sturgeon, which came from four of the five distinct population segments (DPSs; https://www.fisheries.noaa.gov/species/atlantic-sturgeon): the New York Bight DPS, Chesapeake Bay DPS, Carolina DPS, and South Atlantic DPS. Atlantic Sturgeon from the Gulf of Maine DPS were not detected in our study. The ability of Atlantic Sturgeon to travel long distances and to navigate the Cape Hatteras restriction was documented by our strategically placed array.

Our results describing winter presence and purported migratory movements are supported by observations in earlier studies, which targeted Atlantic Sturgeon or caught them incidentally during surveys. Holland and Yelverton (1973) tagged and released Atlantic Sturgeon off North Carolina during winter months (November–February), and most were in shallow waters 0–18 m deep between Cape Lookout and the Virginia border to the north. While conducting an inshore anadromous survey in 1978, Johnson et al. (1978) captured five Atlantic Sturgeon in February from 7–12-m depths less than 2 km from shore. Stein et al. (2004) also reported the presence of Atlantic Sturgeon off North Carolina, mainly inside the 25-m isobath and primarily associated with inlets. Results of the annual Cooperative Winter Tagging Cruises described by Laney et al. (2007) captured 146 juvenile Atlantic Sturgeon in bottom trawls from approximately 9–21-m depths. Genetic testing of the fin clips collected from these fish indicated that they were of mixed origin. More recent analysis of the entire Atlantic Sturgeon data set (1988–2016) from the Cooperative Winter Tagging Cruises indicated that the average depth of capture was 15.3 m (mode = 12.8 m), with a range of 7.3–25.0 m (R. W. Laney, U.S. Fish and Wildlife Service (retired) and B. R. Versak, Maryland Department of Natural Resources, personal communication). Furthermore, Laney et al. (2007) noted evidence of aggregation or schooling.

Relationships between Atlantic Sturgeon presence likelihood and both air temperature and SST were similar to those we found for Spiny Dogfish, suggesting that Atlantic Sturgeon may associate with the same coldwater masses. If this is the case, then there is potential for interactions between Atlantic Sturgeon and local fisheries targeting Spiny Dogfish. However, maximum presence likelihood of Atlantic Sturgeon was associated with lower air temperature and SST than that of Spiny Dogfish, so targeting Spiny Dogfish in the warmer part of their preferred temperature range may reduce the chance of Atlantic Sturgeon bycatch.

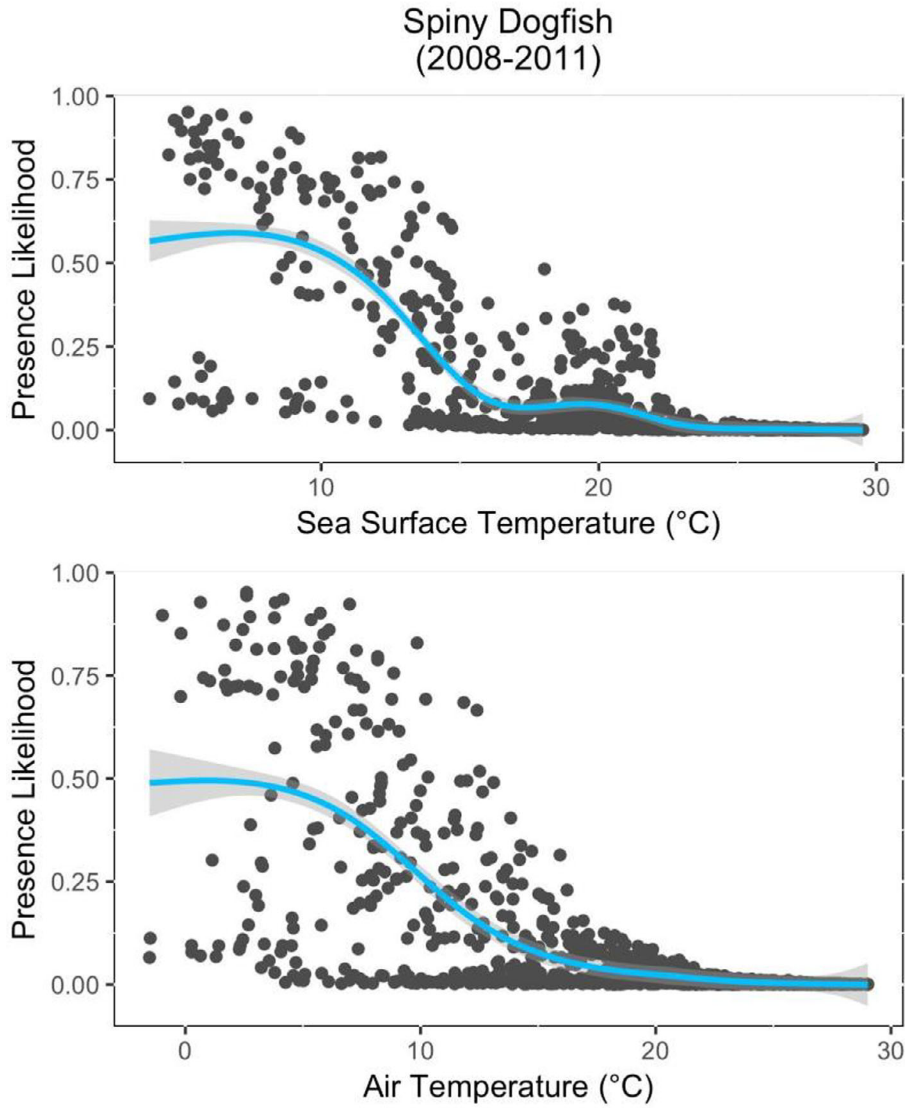

FIGURE 4. Predicted presence likelihood in relation to sea surface temperature and air temperature for Spiny Dogfish based on binomial generalized linear model results using acoustic tag detections and associated environmental data from the 2008–2011 deployment of the Cape Hatteras array. Lines are smoothed trend lines (locally weighted scatterplot smoothing) showing SE.

Sandbar Shark

Although the low sample size of tag detections likely prevented GLM results from identifying significant relationships between Sandbar Shark presence and any of the environmental variables we analyzed, tag detections did confirm late-winter presence of this species in the array area. Cape Hatteras has long been identified as part of the overwintering habitat for Sandbar Sharks originating from northern nursery habitats in Chesapeake and Delaware bays (Grubbs et al. 2007; McCandless et al. 2007; Conrath and Musick 2008). The concentration of juvenile Sandbar Sharks at this location during the winter was part of the justification for establishing the Mid-Atlantic Shark Closed Area, which closes most of the continental shelf off North Carolina to bottom longline gear from January through July (NMFS 2003). Juvenile Dusky Sharks *Carcharhinus obscurus*, the other species that the time–area closure was intended to protect, also occur within the area during the late fall through early spring (Bangley et al. 2020, this themed issue), as do several other coastal sharks of conservation concern. Both adult and juvenile Sand Tigers *Carcharias taurus* overwinter in the vicinity of Cape Hatteras (Kneebone et al. 2014; Teter et al. 2015). Based on fishery capture and sightings data, White Sharks *Carcharodon carcharias* may occur in coastal North Carolina waters year-round but are most common during fall and spring migrations (Curtis et al. 2014). More recent telemetry work has shown that the Hatteras Bight is a key

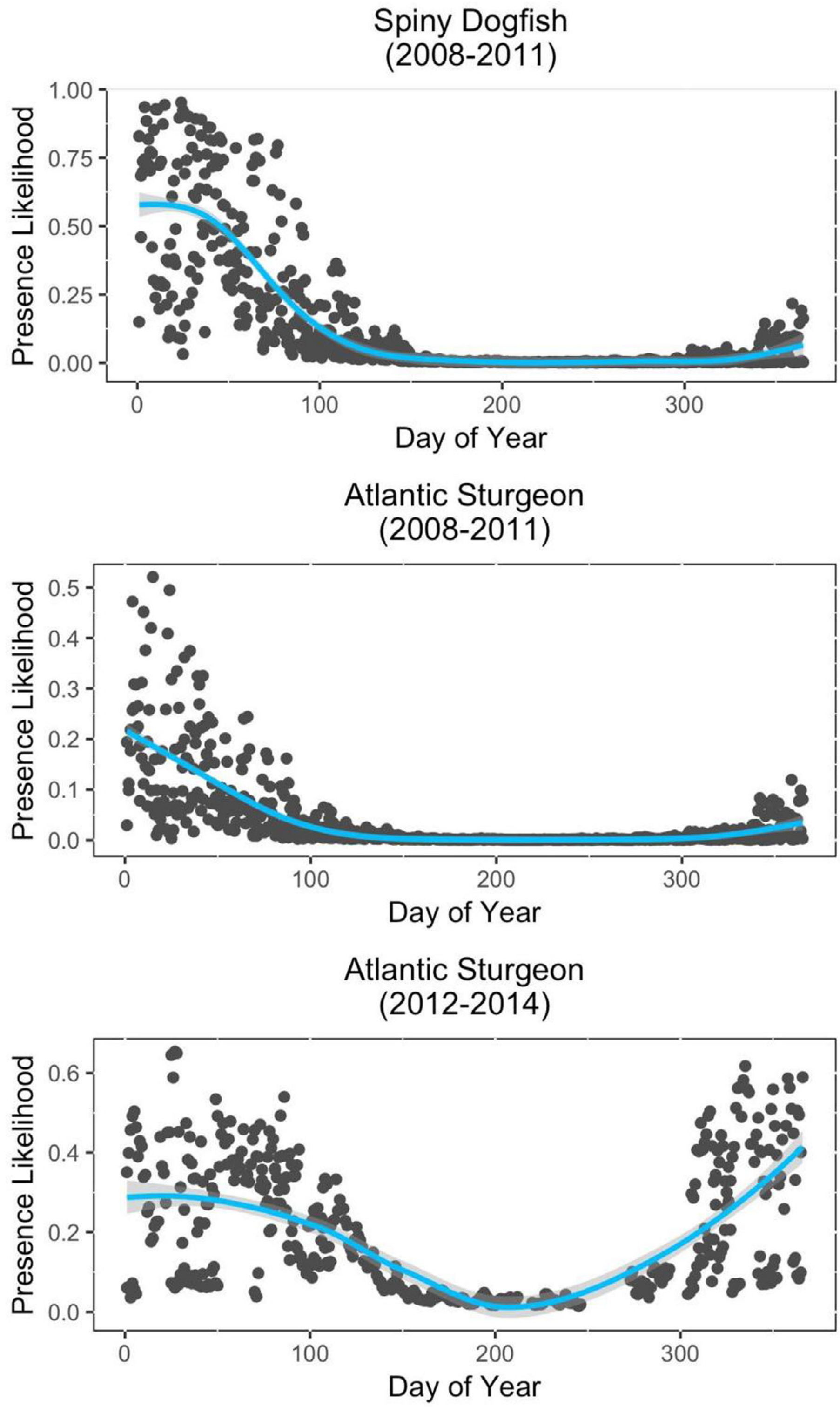

FIGURE 5. Predicted presence likelihood of Spiny Dogfish and Atlantic Sturgeon in relation to day of year based on binomial generalized linear model results applied to environmental data from the 2008–2011 and 2012–2014 deployments of the Cape Hatteras acoustic array. Lines are smoothed trend lines (locally weighted scatterplot smoothing) showing SE.

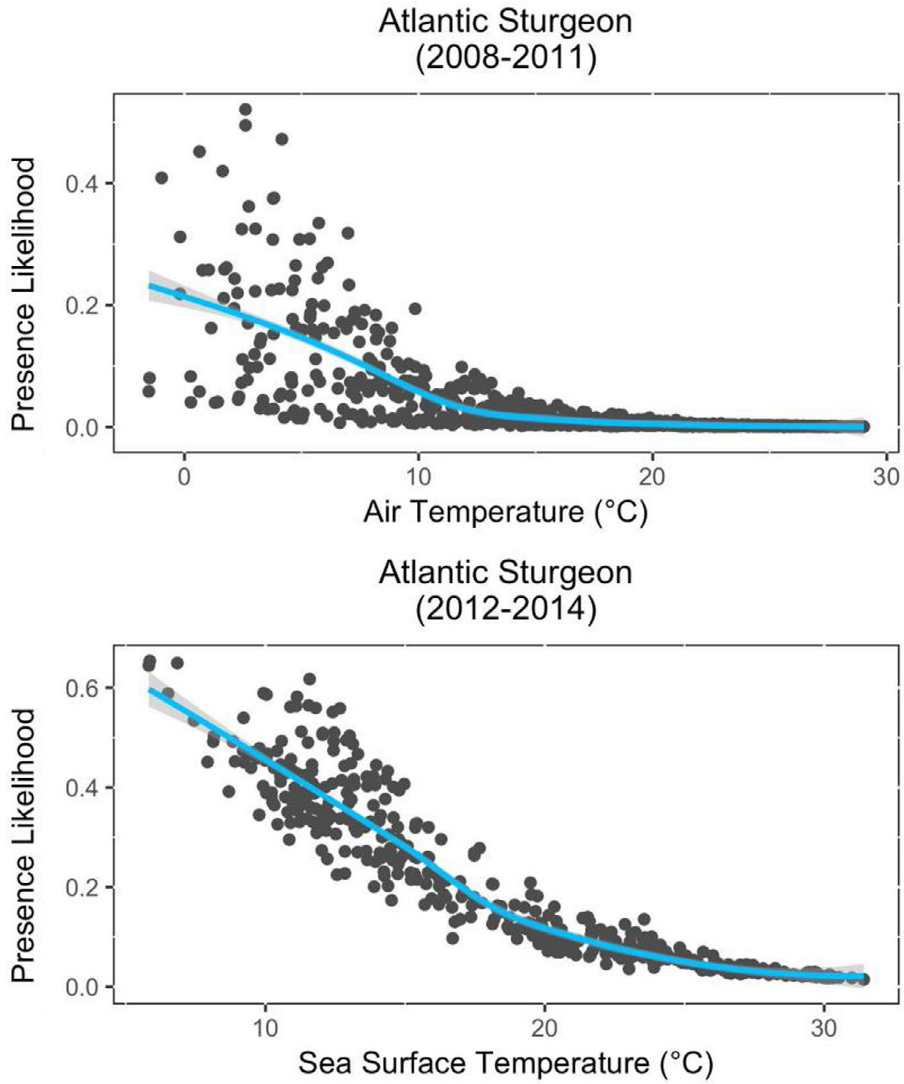

FIGURE 6. Predicted presence likelihood for Atlantic Sturgeon in relation to air temperature and sea surface temperature based on binomial generalized linear model results using acoustic tag detections and associated environmental data from the 2008–2011 and 2012–2014 deployments of the Cape Hatteras array. Lines are smoothed trend lines (locally weighted scatterplot smoothing) showing SE.

feature in the coastal portion of the annual migration of adult White Sharks (Skomal et al. 2017); juveniles may overwinter on the continental shelf off North Carolina in considerable numbers (Curtis et al. 2018). A wide variety of other shark species also occurs off Cape Hatteras during winter, where despite the closure of bottom longline fishing they can comprise a considerable amount of the targeted catch and bycatch in gill-net fisheries (Jensen and Hopkins 2001; Thorpe and Frierson 2009). Redeployment of an acoustic array at this location in the future could substantially improve our understanding of habitat use by these and other species.

Concluding Remarks

Although our work provides a simple framework for showing the seasonal presence patterns of several species, it also serves as a baseline for environmental factors associated with their presence and may offer future insight into changes in offshore habitats associated with climate change, which is a current concern for fishery management in the U.S. northeast continental shelf (Nye et al. 2009). In addition, our results validate the importance of a strategically placed array in effectively intercepting these species, which migrated through the biogeographic boundary and into the study area. The strength of acoustic arrays placed at strategic locations along the continental shelf could be enhanced by using them in concert with more traditional surveys employing commercial gear (e.g., trawls, longlines, and sink gill nets) and the integration of remote sensing (e.g., White et al. 2016; Taylor and Lembke 2017; Goodoni et al. 2018; Luczkovich et al. 2019), modeling, and ocean observing at the seascape level (Kavanaugh et al. 2016). As future technology continues to evolve, biological survey information on continental shelf habitats will increase in quality and quantity to enhance our understanding of species interactions and continental shelf migratory pathways, which BOEM has listed as a top priority for current and future anthropogenic activities, including (but not limited to) the seasonal timing of coastal sand mining, inlet dredging, and exploration of oil and gas deposits.

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