ASSOCIATING FISH TAG DETECTIONS TO SATELLITE DERIVED WATER MASSES AND OCEAN FRONT GRADIENTS

By

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ABSTRACT OF THE THESIS

Associating fish tag detections to satellite derived water masses and ocean front gradients

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Marine fish habitats are defined by both dynamic water column properties and static benthic features. Fish move to stay within suitable oceanographic conditions, making it crucial to track water masses due to shifting habitat ranges. Ocean characteristics like temperature and color that differentiate water masses and the boundaries between them can track these dynamic habitats. This analysis investigates the distribution of fish and species by water mass and the fronts between them, examining their relationship in terms of stratified versus unstratified water column conditions. Acoustic tag detections of fish from 10 separate Slocum glider missions between 2020 – 2022 are compared to water masses and ocean fronts. Biological data, for the tags detected, was compiled by requested information from tag owners. The concurrent temperature, density, salinity, O2 concentration and saturation, water depth, chromatic dissolved organic materiel (CDOM), and chlorophyll-a from the glider sensors provide context for interpreting the movement and distribution of the tagged fish in relation to evolving water column properties.

Additionally, water mass and ocean fronts matched to the glider-based fish detections, were derived from NASA's MODIS-Aqua satellite data between 2020 – 2022 in 1-day composites. This product defines water masses and fronts between them based on observed SST and OC[1, 2]. A water gradient strength/distance index score was created by taking the water gradient strength score and dividing by the distance between the detection and the front. The index score is used to determine if there is an association between fish and ocean fronts.

Future research will require more detections and filling in the gaps of satellite coverage loss to better understand fish distribution across a wider range of ocean conditions. While lack of available data constrained this study in producing viable results, it served as a proof of concept that this method can be employed. Incorporating species' associations with water masses and ocean fronts into biomass estimates during stock assessments could improve the accuracy.

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Connecticut's Department of Energy and Environmental Protection (CT DEEP)/ Affiliated with Connecticut's Department of Energy and Environmental Protection (CT DEEP)), Bill Post/Ellen Walldrop (Diadromous Fishes Coordinator – South Carolina Department of Natural Resources/ Affiliated with South Carolina Department of Natural Resources), Tobey Curtis (Fishery Management Specialist - Atlantic Highly Migratory Species Management Division, NOAA Fisheries), Jason Rock/Ami Staples (Biologist Supervisor – North Carolina (NC) Division of Marine Fisheries /Marine Fisheries Biologist II - Multi-species Tagging Program, Fisheries Management | NC Division of Marine Fisheries), and John Dodd (Executive Director – Atlantic Shark Institute)

Thanks to data sharing by the tag owners, out of 66 unique tag ID's detected, the biological dataset included: species data for 46 tags (70%); release locations for 31 tags (47%) as coordinates and 6 tags (9.1%) as general locations (56.1%); release dates and lengths for 35 tags (53%); sexes for 13 tags (19.7%); weights for 4 tags (6.1%); and release times for 3 tags (4.5%).

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1.0 Introduction:

Marine fish habitats are often characterized by stationary seafloor structures, vegetation, and the dynamic water column above. While the seafloor characteristics are more static, the water column is in a near constant state of flux[3-5]. Marine fish shift their distribution to remain within suitable ranges of oceanographic conditions[6-8]. Marine fish habitat range is defined here as the area where suitable oceanographic conditions and known geographical ranges overlap.

Since marine fish habitats change in response to the movement of water, it is important to track water masses that can be defined based on oceanographic conditions such as Sea Surface Temperature (SST) and Ocean Color (OC)[1, 2]. The tracking of dynamic ocean conditions relative to shifting fish distribution will help to inform fish stakeholders where fish are likely located within their geographical habitat range. Improved knowledge of fish habitat can inform fisheries management and improve biomass estimations.

To determine which water masses are preferred by fish and if there is an association of fish distribution with ocean fronts, acoustic tag detections from submersible glider-mounted acoustic receivers must be associated with dynamic ocean characteristics. Fish telemetry allows for the detection of tagged fish by receivers. Receivers can be deployed on fixed moorings or mobile platforms like ocean gliders. A method to map detections relative to satellite derived water masses and ocean fronts to explore species specific overlap with dynamic water column properties was created. Data were organized into two ocean seasons, winter mixed and summer stratified to see if any water mass and ocean front associations were dependent on water column structure[9, 10]. A supplemental analysis was conducted to identify oceanographic variables explaining detected fish distributions. The following sections describe the methods, results, and discuss the implications of the study.

2.0 Methods:

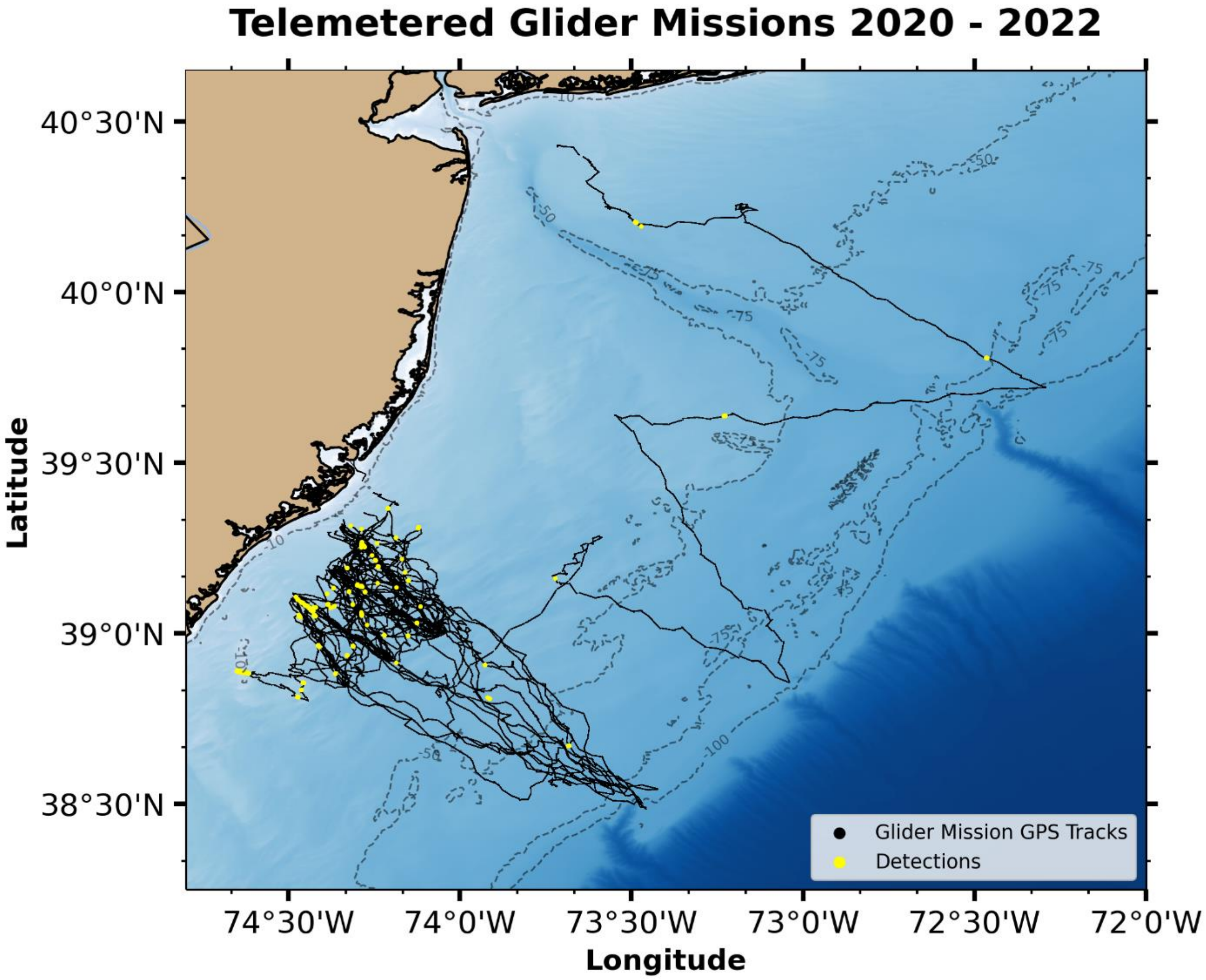

Figure 1. All Slocum Glider missions between 2020 - 2022 where an InnovaSea Vemco acoustic receiver accompanied the glider on its mission. GPS tracks of missions used in this study are shown in black solid lines and tag detections are shown as yellow dots.

2.1 Glider Deployments:

The study used Teledyne's Slocum Gliders, a unique mobile telemetry platform coupling detections with collected oceanographic data from the glider's sensors. The glider moves in a saw tooth pattern, using a buoyancy pump, up and down in the water column, creating a profile transect of sub-surface conditions. Missions typically last 1 – 2 months due to the high efficiency nature of the method of using wings to generate horizontal motion when the glider's buoyancy changes. The gliders collect temperature, density, salinity, O_2 concentration and saturation, water depth, chromatic dissolved organic material (CDOM), and chlorophyll-a on every 3rd downward tooth at intervals of a few seconds, which can provide context for interpreting the distribution of the tagged fish and their relation to water column stratification.

For this research, 10 missions from 2020 – 2022 were examined. All glider missions' GPS tracks are shown in **Figure 1** and yellow dots indicate locations of all raw tag detections. RU34 conducted 9 of these missions while RU28 conducted 1 of them. There were 3 missions by RU34 in 2020, 2 in 2021, and 4 in 2022. The only RU28 mission took place in 2022.

2.2 Acoustic Telemetry:

Fish are surgically implanted with acoustic tags that send out unique identifying acoustic signals at 69 kHz at timed intervals (Vemco, InnovaSea Systems Inc). Those signals are then detected, timestamped, and stored by compatible receivers which decode the unique tag identifier (ID) associated with each unique signal. For a receiver to decode the signal, it must hear the entire signal, which in the case of Vemco transmitter tags is a pulse train of several millisecond bursts. Information is encoded as the time intervals between bursts of a train. Time stamps from logged detections are matched with the time stamps from the glider's GPS record (**Figure 1**).

All detections from the glider mounted receivers were submitted to the Mid-Atlantic Acoustic Telemetry Observation System (MATOS) of the Atlantic Cooperative Telemetry (ACT) network, along with the GPS track of the host glider missions. Time stamps from detections were matched with the glider's GPS records (**Figure 1**). Detections were verified against known tags in MATOS and filtered as “qualified” (tag metadata submitted by the tag owner) or “unqualified” (no record of deployment in MATOS, including unreported tags and false detections). Only 1067 qualified detections out of 33,099 total detections were used in this research and 18 of the qualified detections were used in the analysis.

2.3 Water Masses and Ocean Fronts:

Water containing similar oceanographic conditions, within a continuous geographical area are referred to as water masses[1, 2, 11]. Ocean fronts separate water masses, with the strength determined by the magnitude of difference between the neighboring water mass characteristics on either side of the front [1, 2, 11-13]. For this analysis the water mass characteristics of each grid point in the satellite data were classified based on SST and OC from NASA's MODIS-Aqua satellite using Ward's linkage agglomerative clustering and K-means divisive clustering [1, 2]. The water mass and fronts products have a 1-km resolution and are a 1-day composite [1, 2]. An example of water mass and water gradient products on 11/09/2021, with good satellite coverage, are shown in **Figure 2**.

Water masses are designated 0 – 500, which are categorical labels depending on the measured SST and OC characteristics of each data point in each satellite map [1, 2]. The pixels characterized as fronts are given scores that represent the strength of the ocean front, where the higher the score indicates larger differences in SST and OC in the neighboring water masses, indicating a stronger ocean front[1, 2].

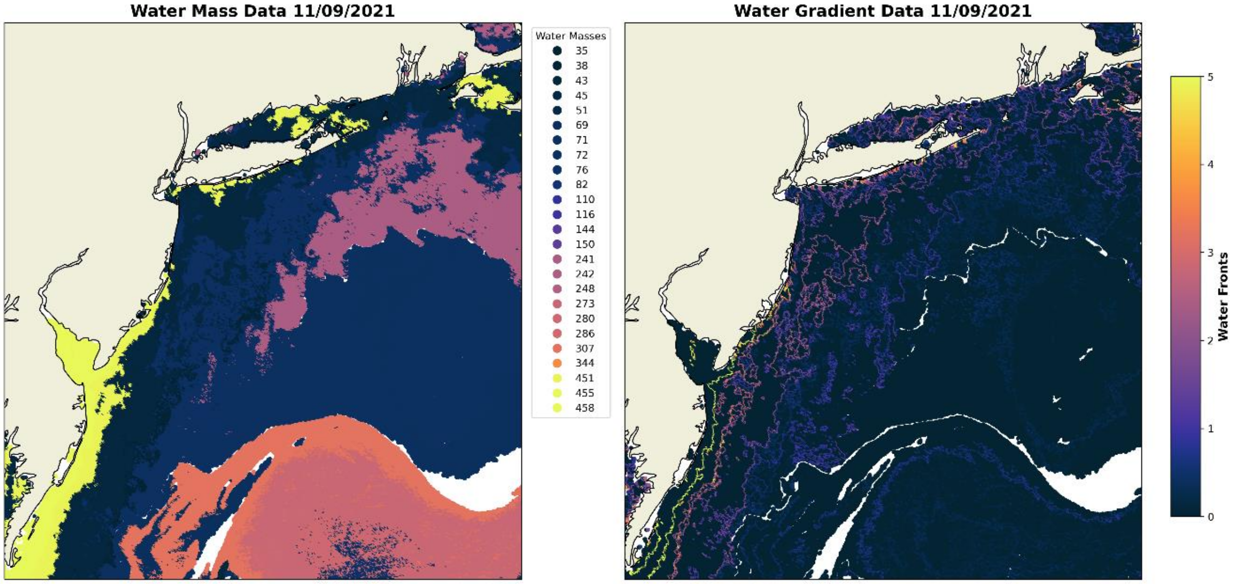

Figure 2. Satellite coverage of the Mid-Atlantic-Bight on 11/09/2021 for the Water Mass and Water Gradient Products measured from SST and OC. The Water Gradient Product color bar was capped at a value of 5 to improve visualization of the Ocean Fronts.

2.4 Association of Fish Detections with Water Masses and Ocean Fronts:

Detection events were treated as a statistical sample unit with the parameters of a) date, b) water mass, c) front strength, d) water column structure (mixed or stratified), and e) species, as described below. Tag detection at 50% efficiency is generally constrained to a 0.6-km radius and is possible to 1 km, so a 1-km radius was chosen to match the resolution of the water mass and water gradient products[14]. To avoid bias from varying detection frequencies among unique tags, only a single detection per day was used, aligning with the 1-day satellite data composites. Exceptions were made if a fish crossed from one water mass to another, necessitating two detections for that day. A 1-km radius grid was created around each detection, assigning a designation (0 – 500) of the most common water mass within that grid (**Figure 3**). Each detection was assigned the nearest recorded water gradient strength score above 0.1 along with the distance, in kilometers, from the detection to the water gradient. This method removed weak fronts with a score below 0.1.

In addition to the absolute value of the closest front to each detection, a second metric was derived to account for both strength and proximity of strong fronts to the detection event. To do this, the Water Gradient Strength/Distance Index was calculated by dividing the water gradient strength score by distance. This new index scores the strength of association between the fish and the ocean front, where a higher score represents an association to a strong front.

This analysis investigates the distribution of fish and species by water masses and ocean fronts during stratified and unstratified ocean seasons. By examining the range between the most recent surface and bottom density readings from the glider at the time of tag detection, the ocean season is considered stratified if the range is ≥ 0.5 kg/m^3 [9, 10].

All data manipulation, processing and analysis was done in the Python coding language using the Jupyter Lab Notebook. Commented scripts are available at: https://github.com/ScottPescatore

2.5 Principal Component Analysis (PCA) on Glider Oceanographic Data:

Complimenting the spatial surface ocean characteristics provided by the water mass products described above, the glider derived data was examined to determine the influence of subsurface ocean characteristics. Distribution of species detected by the glider was fitted to subsurface oceanographic data using Principal Component Analysis (PCA) in Canoco 5 (v5.12). This separate analysis used all qualified detections, regardless of satellite coverage and put them into 10-minute bins to reduce detection frequency bias. The detection was then assigned the averages of the glider derived O_2 saturation/concentration, temperature, salinity, depth, density, CDOM, and chl-a within each time bin.

3.0 Results:

3.1 Glider Missions, Fish Tag Detections, and Satellite Coverage

Out of the 10 available missions, 5 missions (3 missions in 2020 and 2 missions in 2022) were used in the final analysis, due to lack in satellite coverage or a tag lacking species data. Over the 10 available glider missions, tag detections occurred on 48 unique dates. Of these, 13 days (27.1%) had satellite coverage within 1 km for the water mass product, and 9 days (18.75%) were used in the final analysis. Out of 66 unique tags detected, 20 (30%) species were unknown and therefore dropped from the final analysis. Ultimately, only 18 detections, or 1.7% of 1067, were used in the final analysis.

3.2 Water Masses, Ocean Fronts, and Fish Tag Detections

The species-specific distribution relative to observed water masses and fronts in the mixed and stratified seasons are shown in **Figure 3 and 4**. 2 water masses had 3 or more individuals detected within them (**Figure 3**). Water mass 51 (SST ~7 °C) had 6 Striped Bass detected within it and water mass 455 (SST ~20 °C) had 3 Atlantic Sturgeon detected within it.

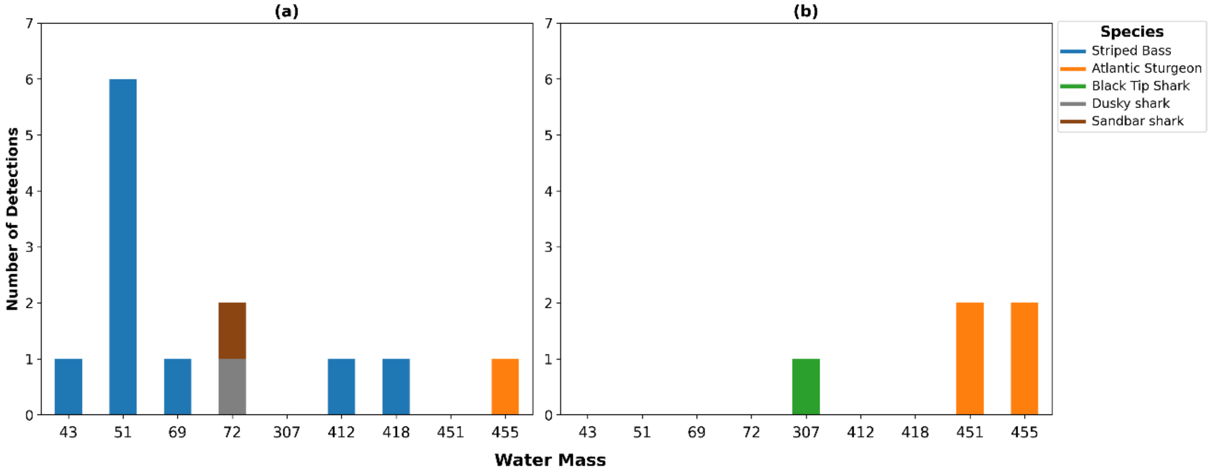

Figure 3. The distribution of fish species by Water Mass during mixed (a) and stratified (b) ocean seasons.

Following previous studies, strong fronts are defined by values of at least 1.5 on the water gradient strength score[11]. Of the 18 detections for all fishes in both ocean seasons, 12, or 66%, were found near strong ocean fronts (**Figure 4**(**a**) & (**b**)). There was no difference in percentage of detections near strong ocean fronts between the mixed (**Figure 4**(**a**)) and stratified ocean seasons (**Figure 4**(**b**)). 100% of detected Atlantic Sturgeon and 60% of detected Striped Bass were near strong ocean fronts.

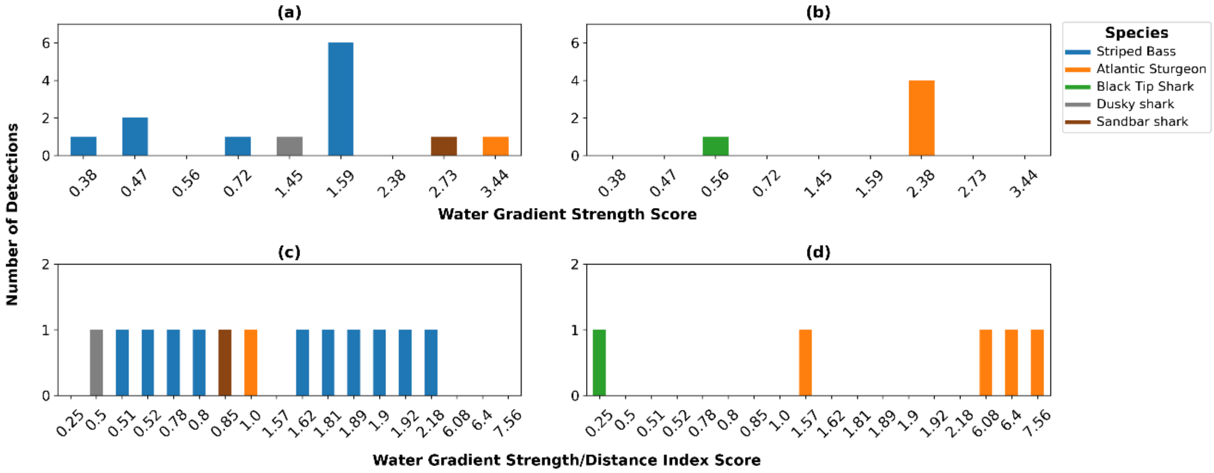

Figure 4. The distribution of fish species by nearest Water Gradient Score > 0.1 during mixed (a) and stratified (b) ocean seasons. The distribution of fish species by the Ocean Front Strength/Distance Index Score (Nearest Water Gradient Score > 0.1 / Distance (km)) during mixed (c) and stratified (d) ocean seasons.

Comparing the fish detections against the combined front strength and distance metric we see similar trends. As a reminder with this metric, a front 1 km away scored at 1.5 will have the same score of 1.5 as a stronger front 2 km away scored at 3. Like the prior metric, we assigned an index score above 1.5 as a feature strong or close enough to be ecologically relevant. Of the 18 detections for all fishes, 10 (56%) had an association with these stronger ocean fronts. For the mixed ocean season (**Figure 4**(**c**)), 6 Striped Bass (60%) have an association with stronger ocean fronts, while for the stratified ocean season (**Figure 4**(**d**)), 4 Atlantic Sturgeon (50%) have an association with stronger ocean fronts. 60% of Striped Bass detected had associations with stronger ocean fronts. For Atlantic Sturgeon, 80% had associations with stronger ocean fronts. All sharks detected had relatively low associations with ocean fronts.

3.3 Glider Oceanographic Data and Fish Tag Detections:

Principal Component 1(PC 1) explains 90.28% of covariance among the detection data while PC 1 & 2 together explain 97.3% of the covariance. The variables that had the most influence for PC 1 were depth, salinity, and O_2 saturation and for PC 2 were CDOM, chl-a, and salinity. The variables of density, O_2 concentration, and temperature had little influence on explaining the covariance among the detection data.

4.0 Discussion:

The purpose of this study was to develop a methodology for determining if fish associate with surface and subsurface ocean features. This study demonstrated that it is feasible to associate tag detections to water masses and ocean fronts, providing insights into how fish interact with their dynamic environment. This enables tracking a fish's preferred habitat as it changes and they move to remain within it[3, 5, 15, 16]. Satellite products, like the water mass and water gradient products, cover large geospatial areas in relatively small timescales (1-day composites) and provide ecologically relevant evolving maps that provide context for tracking fish in complex coastal systems. The ability to track water masses via satellite was the first step, now this study has set up a methodology that associates detections of fish within this evolving ocean habitat to determine if fish favor specific water masses and how strongly they are associated with strong ocean fronts. All software developed under this thesis has been shared so that future work can utilize and adapt it to their needs.

Additionally, mobile platforms like gliders allow for association of subsurface ocean conditions with concurrent fish detections. Similar methods have been employed to track Atlantic Sturgeon, determine how the seasonal migrations of North Atlantic Right Whales are influenced by ocean features, and improve biomass estimates for a stock assessment of the American Butterfish in the past[11, 15, 17-19]. A heat map product, supported by these concurrent data, was created for use by commercial fishing stakeholders to communicate where Atlantic Sturgeon are likely to be located based on water masses. This predictive tool is significant because Atlantic Sturgeon are classified as 'Endangered' by the federal government and are actively avoided to minimize bycatch, which can lead to a cease in operations or a fine[17, 19, 20].

Another study investigating the influence of ocean features on North Atlantic Right Whales' seasonal migrations used the same water mass and water gradient satellite products and the environmental data from the glider to investigate associations of ocean features with seasonal migration[11]. While the subsurface analysis results were inconclusive, the surface analysis results indicated that North Atlantic Right Whales were more likely to be detected near ocean fronts with strong gradients[11].

While this study provided a methodology, more concurrent data is needed to support more conclusive ecological associations. When interpreting these data, it is important to note that 6 detections of Striped Bass in water mass 51occur on the same day in 2020 and within ~1 km of each other. Of the 5 detections for Atlantic Sturgeon, 4 were detected on the same day within ~1 km of each other in water masses 451 and 455.

While this methodology shows promise, the ecological associations in these 5 glider missions were inconclusive. This is driven by insufficient data to reach statistical significance because of the limitations that include satellite coverage loss due to cloud interference and small sample size of detections. Additionally, the satellite products used here are based on the MODIS satellite that reached its end of life in October 2022. To make up for satellite coverage loss due to clouds, new satellite products and hindcast models using surface currents and other inputs such as gliders and buoys could be created. This would allow for a higher percentage of detections to be compared to water masses and ocean fronts. The algorithm that creates the satellite products could be applied to a new satellite that has the same, or better, sensors used by the satellite to measure SST and OC. If not achievable, a new water mass and water gradient satellite product should be utilized in its place. Collaborating with other researchers that have arrays offshore and increased tagging activity across the community will continue to expand the likelihood of detection by platforms of opportunity like gliders. This would enable more detections to be utilized in future analyses. This analysis highlights the potential for rapid advances in the understanding of these dynamic coastal environments when different observing platforms are brought together.

5.0 Conclusion:

Fish tag detections from gliders were matched with satellite products to determine if fish favor certain water masses and if they have a strong association to strong ocean fronts. While this method can be improved with more input datasets, it currently provides some valuable insight with new, or a continuation of, water mass and water gradient products being created. Due to the limitations on available data, no conclusions were able to be drawn as to if any water masses are favored by fishes or by a specific species or if they have associations with strong ocean fronts, however, this study provides the foundation to gather enough data to make further study feasible. This study provides a basis for accounting for shifting marine fish habitat within their geographic range when tracking fish and has potential to improve biomass estimations for stock assessments and inform fisheries stakeholders[18].

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