



Variation in Temperature, Change in Barometric Pressure, and Salinity Explain Trends in the Acoustic Backscatter of Fishes Within a Large Ship Channel Inlet in the Gulf of Mexico

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Abstract

Human-fortified ship channel inlets can represent the only connection between estuarine and coastal waters for tens of kilometers in some areas of the Northern Gulf of Mexico, making them bottlenecks for fish movement. A variety of fishes associate with the jetties that fortify ship channel inlets, and the deep depths of channel inlets relative to surrounding waters may provide a unique type of habitat. To understand variability in fish biomass in these vital areas, 49 hydroacoustic surveys of the Aransas Channel Inlet, Texas were conducted and paired with environmental (e.g., temperature) and meteorological (e.g., barometric pressure) data between January 2018 and February 2020. Fishery-independent and fishery-dependent data from the surrounding area were employed to provide context to variability in fish backscatter (i.e., volume backscattering strength, s_v , a proxy for fish biomass). Generalized additive models indicated that variation in fish backscatter was best explained by variation in temperature, change in barometric pressure, and salinity (adj.- $R^2 = 0.71$). There were two dimensions to these effects. In the first, variation in temperature tracked seasonal shifts in the relative abundance of pelagic fishes, which were well sampled by acoustic technologies relative to demersal fishes. In the second, episodic cold fronts (i.e., high pressure systems) were associated with high values of fish backscatter — likely because the Aransas Channel Inlet is far deeper than surrounding areas and protected by jetties, making it less affected by physical disturbances and rapidly changing air temperatures or precipitation. Thus, disturbances in the Aransas Channel Inlet (e.g., dredging and construction, shipping traffic) are likely to be most impactful to non-demersal fishes when temperature and salinity are low (<c.a. 15 °C and <c.a. 28 psu) and frontal systems are likely to affect the area (barometric pressure increase >c.a. 3 mb or decrease >7 mb over 24 h).

Keywords Channel inlet · Gulf of Mexico · Fish · Hydroacoustics · Frontal systems · Environmental drivers

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Introduction

Human-made ship channel inlets and the jetties that line them are prominent features on the coastline of many port cities in the US Gulf of Mexico (GOM). In such coastal systems, ship channel inlets cut through barrier islands and offer the only connection between the coastal ocean and bays and estuaries for tens of kilometers. Such channel inlets represent vital connections between those areas for marine life. Channel and bay inlets have been identified as crucial habitat for multi-species fish spawning aggregations (Grüss et al. 2018a, b; Heyman et al. 2019), as the jetties that often line ship channel inlets provide high-relief, hard substrate for fishes to spawn around and high flow rates disperse eggs and larvae into nearby estuaries, which often serve as nursery habitats. As such,

some ship channel inlets may be vital intersections of the ‘migration triangle’ (Harden Jones 1968; Cushing 1982; Secor 2015) for coastal and estuarine fishes. For example, Red Drum (*Sciaenops ocellatus*) adults spawn at the mouths of estuaries and channels (Peters and McMichael 1987; Holt 2008; Lowerre-Barbieri et al. 2008), after which their eggs and larvae are advected into and dispersed within the estuary (Brown et al. 2004). Red Drum mature into juveniles within the estuary (Holt et al. 1983; Rooker and Holt 1997; Winner et al. 2014), then typically move to nearshore areas — likely through the same estuary or channel inlet they were spawned in — to their adult habitat (Rooker et al. 2010; Winner et al. 2014; Lowerre-Barbieri et al. 2016). Atlantic Croaker (*Micropogonias undulatus*), Black Drum (*Pogonias chromis*), Sheepshead (*Archosargus probatocephalus*), Southern Flounder (*Paralichthys lethostigma*), and Spotted Seatrout (*Cynoscion nebulosus*) are other species that are known to utilize channel inlets in spawning or spawning and ontogenetic migrations (Heyman et al. 2019). In addition to fish eggs and larvae, other types of organic matter and nutrients are circulated within and through ship channel inlets, making them productivity hotspots that affect the ecology of wider areas (Santora et al. 2017).

The coastal and estuarine waters of the GOM, where ship channel inlets are located, experience considerable variation in environmental conditions (Bianchi et al. 1998; Barkan et al. 2017; Baumann and Smith 2018). These areas are affected by extreme episodic frontal systems (e.g., cold fronts, hurricanes) that rapidly change conditions (Flint 1985; Bianchi et al. 1998; Lin et al. 2016) and are subject to cycles of drought that may exacerbate the effects of extreme events and affect food webs (Palmer and Montagna 2015; Fuiman 2018; McMillan et al. 2018). Such seasonal, episodic, and gradual changes in environmental conditions are known to prompt distribution shifts in coastal and estuarine fishes (e.g., Callihan et al. 2015; Dance and Rooker 2015; Ajemian et al. 2018). While distributional responses to episodic disturbances may be driven by physiological tolerances or the possibility of physical harm (Breitburg 1992; Nathan et al. 2008; Secor 2015; Allen et al. 2018; Lowerre-Barbieri et al. 2021), seasonal shifts in distribution are more often associated with life history events and ecological phenomena that are cued by environmental and physical conditions (Ciannelli et al. 2008; Nathan et al. 2008; Secor 2015; Allen et al. 2018; Lowerre-Barbieri et al. 2021). The degree to which such stimuli prompt realized distribution shifts depends upon physical characteristics and behavioral tendencies (Breitburg 1992; Nathan et al. 2008; Lowerre-Barbieri et al. 2021), such that the effect of a stimulus on a regional community depends upon assemblage composition in affected areas, which may

change throughout the year. Given that many GOM estuaries are lined by barrier islands and channel inlets cover relatively small geographic areas, channel inlets may act as bottlenecks for distribution shifts between coastal and estuarine environments along with providing a unique type of deep, rugose habitat.

The conflicting roles of ensuring safe navigation areas for large vessels, serving as passageways for marine life, providing habitat for fishes, and often being hotspots for recreational fishing make ship channels in the GOM fruitful areas for study. However, there has been little effort to understand the variability in fish biomass in these areas. This is likely due to the numerous challenges of surveying active ship channels (e.g., heavy traffic, low visibility, high currents). Active acoustic surveys are uniquely positioned to overcome the challenges of studying fishes in ship channels, as data can be collected from a mobile platform in a rapid and non-invasive manner. Collecting data to ‘ground-truth’ (i.e., provide independent biological information for) acoustic surveys in ship channels is more challenging given that invasive methods (e.g., trawling) might disrupt marine traffic and non-invasive methods (e.g., video surveys) typically require good visibility, low currents, and minimal ship traffic. While making inferences at the species level with acoustic data typically requires contemporaneous ground-truthing data, applying thresholds to acoustic data can facilitate inferences on general taxonomic groups (e.g., including data from fishes and excluding data from planktonic scattering sources) (Boswell et al. 2007; Simmonds and MacLennan 2008; Rudstam et al. 2009).

The objective of this study was to examine linkages between variability in volume backscattering strength — a commonly used proxy for biomass (Simmonds and MacLennan 2008; Boswell et al. 2010; Egerton et al. 2018), hereafter simply ‘acoustic backscatter’ — that could reasonably be associated with fishes and variability in environmental and meteorological conditions in the Aransas Channel Inlet in Port Aransas, TX, USA (also known as the Aransas Tidal Inlet and the Aransas Pass). It was not possible to collect direct ground-truthing data for the acoustic surveys we conducted, but we used data from a regional fishery-independent monitoring program and local recreational fisheries as well as information about the behavior and life history of common local fishes to provide context to the relationships we described. The effects of environmental and meteorological conditions on fishes within the Aransas Channel Inlet that we described could be used to plan development, maintenance, and shipping activities in channel inlets at times when some groups of fishes may be least disrupted. This information is vital to ensuring the coexistence of valuable recreational fishing (\$122.7 million

in the Corpus Christi and Aransas Bay systems in 2016, Ropicki et al. 2016a, b) and shipping (\$29.5 billion through the Port of Corpus Christi in 2018, Texas Comptroller of Public Accounts 2018, available from: <https://comptroller.texas.gov/economy/economic-data/ports/corpus-christi.php#en1>) industries that support the livelihoods of communities in the Texas Coastal Bend, considering that fishery species depend on the Aransas Channel Inlet for spawning habitat and as the only connection between the coastal and estuarine habitats for tens of kilometers, and shipping traffic to the Port of Corpus Christi passes through the Aransas Channel Inlet. Recent proposals for channel deepening, widening, and installation of a desalination plant and Very Large Crude Carrier (VLCC) terminal at Harbor Island on the bayward end of the Aransas Channel Inlet (summarized in Chenevert et al. 2019; TCEQ proposal WQ0005253000; USEPA proposal TX0138347; USACE proposal SWG-2019-00067; USACE proposal SWG-2019-00245) may disrupt this important area and could have far-reaching consequences, so making inferences on optimal and sub-optimal timing for these activities is critical.

Methods

Site Description

Forty-nine hydroacoustic and sonde surveys were conducted in the Aransas Channel Inlet, Texas, from January 2018 to February 2020 (Fig. 1). The Aransas Channel Inlet is located in Port Aransas, along the central coast of Texas, and was about 400–500 m wide and 15–18 m deep at its center at the time of the study. The channel inlet is fortified by jetties that extend about 1 km from shore and connects the Corpus Christi, Nueces, Aransas, Redfish, Copano, and St. Charles bays to the GOM via the Corpus Christi Ship Channel, Aransas Channel, and Lydia Ann Channel.

Acoustic Data Collection

A Simrad EK80 echosounder with a 120 kHz split-beam transducer (circular beam width of 6.8°; pulse duration of 0.128 ms; ping rate set at maximum) was used for hydroacoustic surveys. The transducer was mounted on the side of

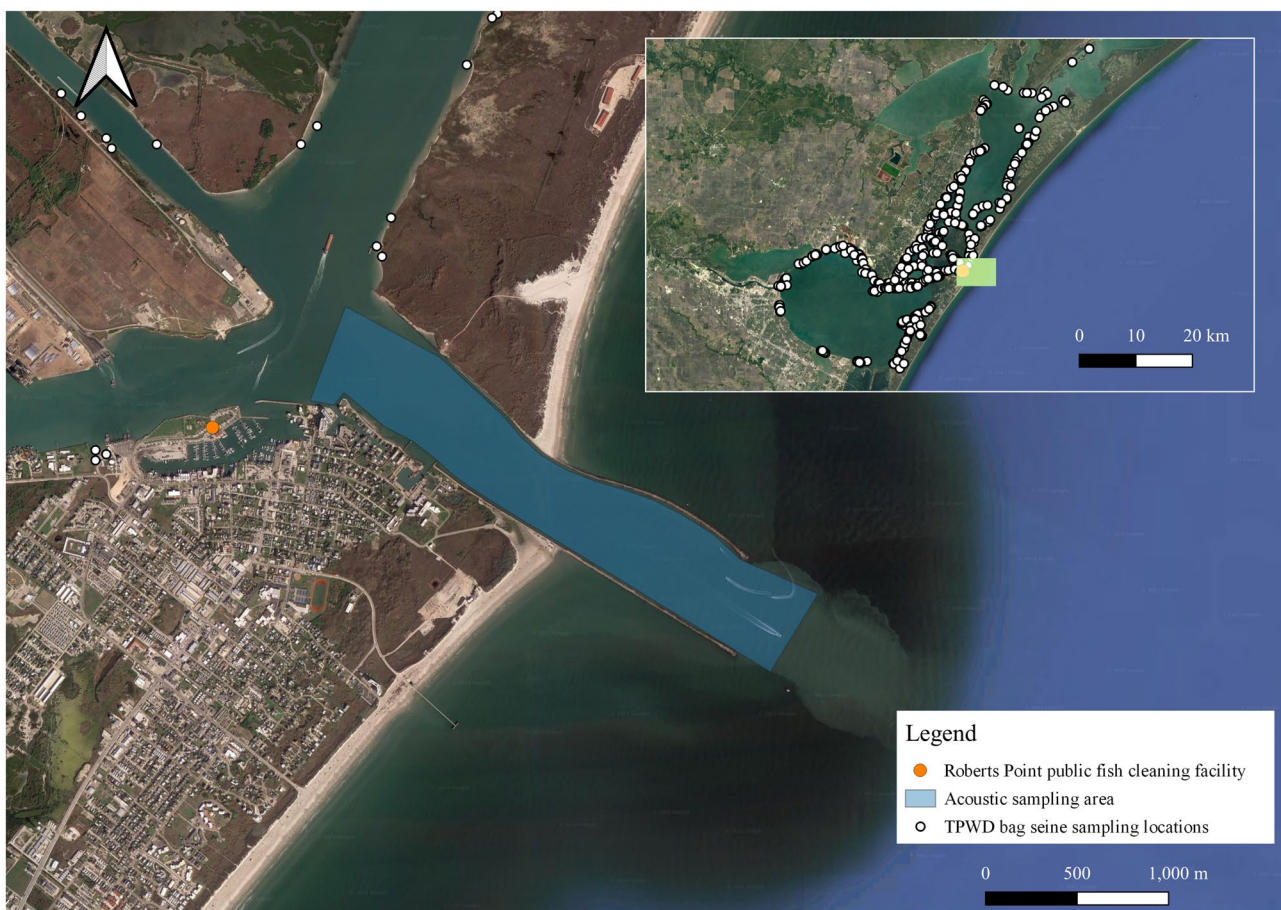


Fig. 1 Study area and sampling locations

the survey vessel on a pole with the transducer angled vertically at 1 m depth. Progressing from the bayward (western) end of the channel to the seaward (eastern) end, the survey vessel conducted 22 parallel transects that were spaced about 100 m apart. Transect length varied from about 350 to 400 m based on safe navigable depths and distances from shore. The vessel traveled at a speed of about 4 kts, with slight variations dependent on current and sea state. On 14 instances, high wave action on the seaward end of the channel, which would have affected the quality of the data and put the equipment at risk, prevented the completion of the full number of transects (see supplementary information S1 for survey dates and number of transect completed for instances in which less than 22 transects were conducted). The echosounder was calibrated according to standard methods (Demer et al. 2015) using a tungsten carbide sphere on about a monthly basis. Hydroacoustic data were geo-referenced with a Garmin GPS and recorded on a laptop computer.

Environmental and Meteorological Data Collection

To collect environmental data, a YSI EXO sonde was deployed at the start and end of the survey. The sonde was allowed to drop directly down to the seafloor, after which it was immediately retrieved. Data were collected throughout the water column, and variables recorded included temperature (°C), salinity (psu), and dissolved oxygen (mg/L). These variables were represented as means across the water column in data analysis. Environmental and meteorological data were also retrieved from instruments permanently deployed in the channel (available from: <https://tidesandcurrents.noaa.gov/>). Data retrieved included air temperature, salinity, water height (m), and barometric pressure (mb).

Fishery-Independent Data Collection

The Texas Parks and Wildlife Department (TPWD) conducts fishery-independent bag seine surveys in the bay system adjacent to the study area. This sampling gear selects both pelagic and demersal fishes and is conducted year round in the study area. We examined this data for seasonal shifts in species composition that might impact the relationships we described between the acoustic backscatter of fishes and environmental and meteorological variables.

Bag seine data from the Aransas Bay, Corpus Christi Bay, and Redfish Bay systems were collected as part of the routine TPWD Fisheries Independent Monitoring Program from January 2018 through February 2020. Bag seines were 18.3 m long and 1.8 m wide, with 19 mm stretched nylon mesh in the wings and 13 mm stretched nylon mesh in the bag. Seines were stretched 12.2 m perpendicular to the shoreline and pulled along the contour of the shoreline for 15.2 m such that a total surface area of 0.03 ha was sampled. A

stratified, random sampling design was employed such that 20 seine locations were randomly selected per month in each of the entire Aransas Bay and Corpus Christi Bay (including Redfish Bay) systems (Fig. 1), though seines collected in secondary bay systems (i.e., though located further into the estuary) were excluded from this study to better focus the results in the estuary immediately adjacent to the Aransas Channel Inlet. All specimens >5 mm were identified to species, when possible, and enumerated. Invertebrates, flatfishes, pufferfishes, crypto-benthic fishes, shallow-water or surf-zone-inhabiting fishes, freshwater fishes, and fishes not identified to species were excluded from the analysis of these data, except for menhadens (*Brevoortia* spp.), which were not consistently identified to species (list of observed but excluded organisms included in supplementary material S2). Records for *Brevoortia* spp. and Gulf Menhaden (*Brevoortia patronus*) were combined for the purposes of this analysis. Relative abundance was calculated from catch per unit effort data, and figures show the relative abundance (proportion) of fishes that made up 10% or more of the catch or the most abundant five fishes if five species did not each exceed 10% of the catch.

Fishery-Dependent Data Collection

We also analyzed fishery-dependent data to examine seasonal shifts in species composition that could affect the relationships we described between the acoustic backscatter of fishes and environmental and meteorological variables. From January 2018 to February 2020, fishery-dependent data were collected at the fish cleaning facility at Robert's Point Park in Port Aransas, Texas. Robert's Point Park is adjacent to the city marina and the Aransas Channel Inlet, and is the most easily accessible public fish cleaning facility in the area (Fig. 1). In the facility, fishers clean their catch on tables and discard carcasses in bins under filet tables, which are emptied by City of Port Aransas employees in the morning and, at times, again in the afternoon if the bins filled up. We visited the facility on two mornings per week (Monday and Friday unless extenuating circumstances prevented visits on those days) prior to the morning cleaning. All non-bait fishes (i.e., fishes that had been fileted or whole individuals of a species that was typically fileted) present in the discard bins were identified to the lowest taxonomic level, counted, and included in the final dataset. Occasionally, fishes known to be used as bait in the area (e.g., Pinfish *Lagodon rhomboides*) appeared to have been fileted, but they were not included due to the possibility that they were harvested outside of the region and the inconsistency of their apparent targeting as a fishery species. In the event that partial carcasses were observed, an individual was only counted if the head was attached. Only non-bait, non-flatfish species that are commonly targeted in estuarine and coastal

environments were considered for analysis of these data (list of observed but excluded species included in supplementary material S2). Figures derived from these data show the relative abundance of fishes that made up 10% or more of the catch, or the most abundant five fishes if five species did not each exceed 10% of the catch.

Acoustic Data Processing

Hydroacoustic data was processed with Echoview software (ver. 11). The first 1 m of the water column was excluded to account for the near-field effect of the acoustic transducer and to eliminate bubbles caused by wave action (Simmonds and MacLennan 2008). The first 1 m above the seafloor was also excluded to account for the acoustic dead zone that occurs above the seafloor (Ona and Mitson 1996). Backscatter from bubbles below 1 m, interference from other echosounders (e.g., ADCP mounted on a pier in the channel), and electrical noise were manually excluded by analysts. Background noise was removed using the Echoview background removal operator with a maximum noise value of 125 dB re. 1 m⁻¹ and minimum signal-to-noise ratio of 10 dB re. 1 m⁻¹. A minimum threshold of -61 dB re. 1 m⁻¹ was applied to acoustic backscatter (S_v) data to exclude planktonic and other small, non-fish scattering sources from this analysis. Target strength data were also analyzed to verify that backscatter from single targets was within a range that could be reasonably attributed to fishes (supplementary material S3). A mean acoustic backscatter value was calculated for each transect, and the median value of across transects was chosen to represent acoustic backscatter in a survey for analysis of relationships between acoustic backscatter and physical conditions. S_v values were transformed to s_v (i.e., transformed from decibel units to the linear domain) for these analyses.

Statistical Analysis

All statistical analyses were conducted in R Studio (ver. 3.6.1; R Core Team 2021). We fit a Gaussian generalized additive model (GAM) with a log link function to examine the relationship between acoustic backscatter and environmental and meteorological variables using the “mgcv” R package (ver. 1.8-28; Wood 2011). The distribution and link function were chosen based on analyses of data properties and preliminary model fits. Correlations between potential predictors in the GAM were assessed prior to model fitting. Of predictors that were correlated with one another above an absolute value of 0.7, the predictor with the lowest adjusted R^2 in a single-predictor Gaussian GAM with a log link function was excluded from the initial multiple-predictor GAM (Leathwick et al. 2006; Grüss, Chagaris, et al. 2018a, b, 2020). For predictors included in the model to represent frontal systems (change in temperature, change in barometric pressure,

barometric pressure), time scales from 96 h pre-survey to 48 h post-survey were explored. Of these predictors across different time scales, the one with the highest adjusted R^2 value in a single-predictor Gaussian GAM with a log link function was selected for inclusion in the initial multiple-predictor GAM.

The multiple-predictor GAM was fit in an iterative manner, where the initial model included all possible predictors that were not correlated with one another over the inclusion threshold and the final model included only significant predictors, as indicated by the estimated degrees of freedom (EDF; greater than 0.9) and p -value (alpha = 0.05). To evaluate the GAM, standardized model residuals were assessed for uniformity, overdispersion, and outliers using the DHARMA R package (Hartig 2021). Residuals were also examined to check their independence from the linear predictor and the relationship between the response and fitted values was assessed for linearity using the `gam.check()` function in `mgcv` (Wood 2011). Furthermore, a bootstrapping procedure was implemented in which Spearman rank correlation coefficients (Spearman ρ) between GAM predictions and observed data tested to be significantly different from zero for 1000 datasets (Bolser et al. 2021; Egerton et al. 2021; Grüss et al. 2021). The global adequacy of the model was also tested via a likelihood ratio test between the final model and a null model. To understand the relative importance of each significant predictor in the final model, an index of relative importance was calculated by comparing predictions from the final model with predictions from a model fit to a dataset in which random permutations of data for predictor variables were performed (i.e., random model; Thuiller et al. 2010; Grüss et al. 2019; Bolser et al. 2020). Specifically, relative importance was calculated by subtracting 1 from the Pearson’s correlation coefficient between predictions from the full and random models (Thuiller et al. 2010; Grüss et al. 2019; Bolser et al. 2020).

Results

Predictor Selection

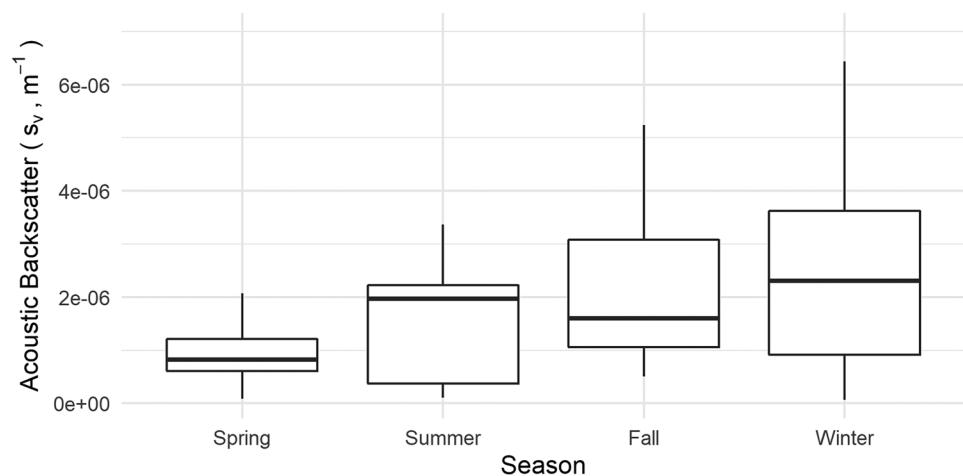
Of the predictors selected to represent the effect of episodic frontal systems (e.g., change in temperature, change in barometric pressure, barometric pressure), change in pressure from 24 h before the survey to the time of the survey was found to be most strongly associated with variation in acoustic backscatter. Dissolved oxygen was correlated with temperature and salinity over the inclusion threshold and was excluded from the initial multiple-predictor GAM based on comparisons between adjusted R^2 values in single-predictor GAMs as described above. Accordingly, the initial multiple-predictor GAM contained the following predictors: water

temperature ($^{\circ}\text{C}$), salinity (psu), water level (m), day of year, and change in barometric pressure over the 24 h preceding the survey (mb).

Trends in Acoustic Backscatter and Generalized Additive Model Results

Median acoustic backscatter was highest in the winter months, followed by summer, fall, and spring months (Fig. 2). Water temperature ($p < 0.0001$; EDF = 2.88), salinity ($p < 0.0001$; EDF = 2.28) and change in barometric pressure ($p < 0.0001$; EDF = 2.63) were retained in the final model, which had an adjusted- R^2 of 0.71 (CI: 0.55–1.00). Temperature had a positive effect on fish acoustic backscatter below $\sim 18^{\circ}\text{C}$ and above $\sim 28^{\circ}\text{C}$, and was the most relatively important predictor in the model (Fig. 3). Change in barometric pressure (i.e., barometric pressure difference) between 24 h before the survey and the time of the survey had a positive effect on fish acoustic backscatter at ~ -6 mb and $\sim +2$ mb, and was the second most important predictor in the model (Fig. 3). Salinity had a positive effect on fish acoustic backscatter below ~ 26 psu and was the least relatively important predictor in the model (Fig. 3). The DHARMA residual diagnostics indicated that the model was correctly specified, as standardized residuals were uniformly distributed, not over or under dispersed, and did not contain significant outliers (Fig. S4.1). Model residuals appeared independent from the linear predictor, and the relationship between response and fitted values was about linear (Fig. S4.2). The Spearman ρ between GAM predictions and observed data was 0.57 (CI: 0.38–0.83) and was significantly different from zero ($p < 0.0001$). The likelihood ratio test indicated a significant difference between the final GAM and null GAM ($p < 0.0001$). These diagnostics indicated the model passed the evaluation tests and could be employed for statistical inference.

Fig. 2 Boxplots of acoustic backscatter by season. These boxplots are defined by the upper and lower quartiles of acoustic backscatter, with the median value shown inside the box



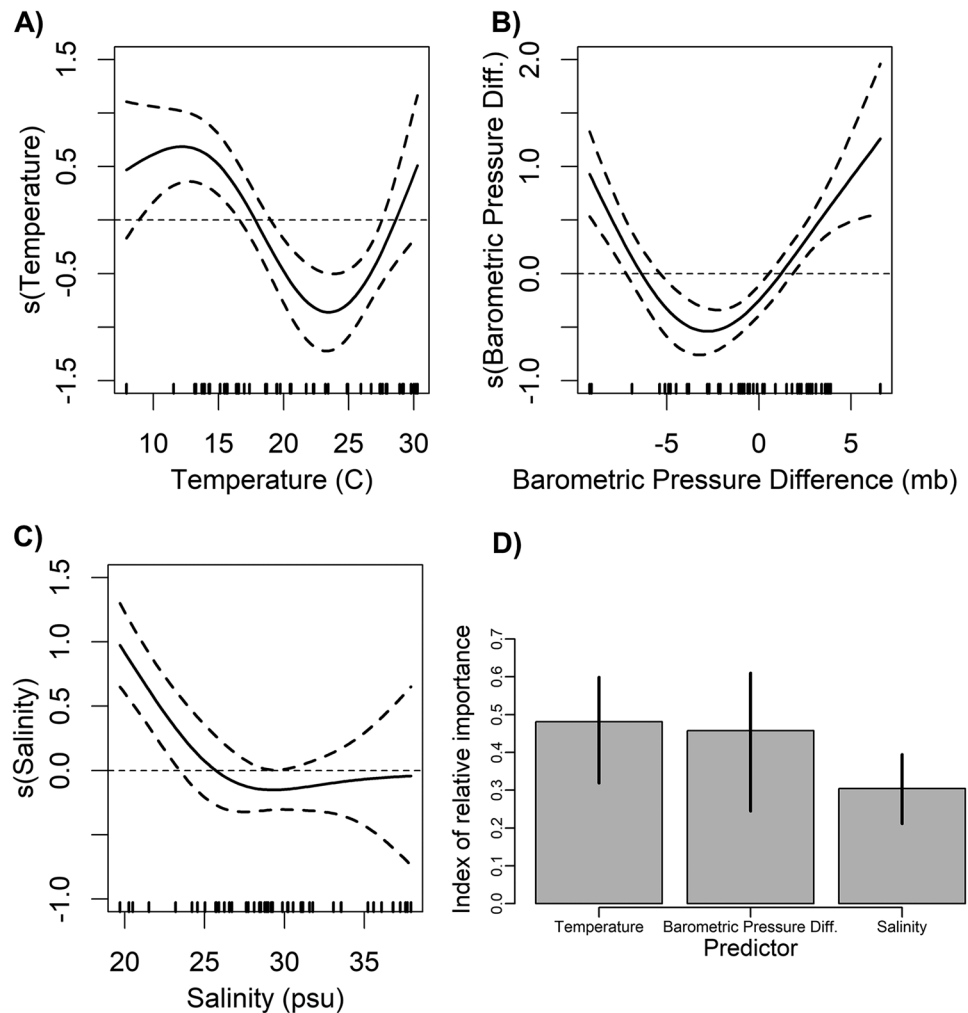
Species Composition from Fishery-Independent Data

Thirty-three fish species or groups of species were retained for analysis of the TPWD bag seine data (supplementary material S2). The group of species refers to Menhadens, which were not consistently identified to the species level. The five most abundant fishes in every season came from a group of 10 (Atlantic Croaker *Micropogonias undulatus*, Atlantic Thread Herring *Opisthonema oglinum*, Bay Anchovy *Anchoa mitchilli*, Menhadens, Pinfish, Red Drum, Scaled Sardine *Harengula jaguana*, Spot *Leiostomus xanthurus*, Striped Mullet *Mugil cephalus*, White Mullet *Mugil curema*; Fig. 4). Pinfish was among the top five most abundant fishes in all seasons, Spot and Bay Anchovy were among the top five most abundant fishes in three of four seasons, and Atlantic Croaker, Menhadens, and White Mullet were among the top five most abundant fishes in two of four seasons (Fig. 4). Pinfish was the most abundant species in spring, summer, and fall, while Spot was the most abundant species in winter (Fig. 4).

Species Composition from Fishery-Dependent Data

Eleven fish species and one group of species were retained for analysis of the fishery-dependent data (supplementary material S2). The group of species refers to Kingfishes (*Menticirrhus* spp.), which were not consistently identified to the species level. The five most abundant fishes in every season came from a group of six (Black Drum *Pogonias cromis*, Gafftop Catfish *Bagre marinus*, Kingfish (*Menticirrhus*) spp., Red Drum, Sheepshead *Archosargus probatocephalus*, Spotted Seatrout *Cynoscion nebulosus*) (Fig. 5). However, their relative abundance varied substantially from season-to-season (Fig. 5). Gafftop Catfish was the most abundant species in the spring, Spotted Seatrout was the most abundant species in the summer, Red Drum was the most abundant

Fig. 3 Marginal effect plots for **A** temperature, **B** barometric pressure difference, and **C** salinity, and **D** bar plots of the index of relative importance for significant predictors in the Gaussian GAM of fish acoustic backscatter. Hash marks on the x-axis indicate observed values of each predictor in panels A–C. Lines intersecting bar plots show confidence intervals around the indices of relative importance in panel D



species in the fall, and Sheepshead was the most abundant species in the winter (Fig. 5).

Discussion

In the GOM, ship channel inlets are important areas as they are often the sole connections between estuarine habitats and the coastal ocean for tens of kilometers, in addition to providing spawning habitat for many fishes (Grüss et al. 2018a, b; Heyman et al. 2019). Fish life history events (e.g., spawning, seasonal migrations) are typically cued by environmental conditions that vary among species (Ciannelli et al. 2008; Nathan et al. 2008; Secor 2015; Allen et al. 2018; Lowerre-Barbieri et al. 2021). Acute distribution shifts of fishes are also prompted by variations in environmental and meteorological conditions (Breitburg 1992; Nathan et al. 2008; Secor 2015; Allen et al. 2018; Lowerre-Barbieri et al. 2021). Since responses to environmental and meteorological conditions and the timing of life history events vary among species, understanding variation in fish biomass in general

within channel inlets under different conditions requires direct study. We found that variation in water temperature, change in barometric pressure, and salinity are influential in explaining variation in acoustic backscatter — a commonly used proxy for biomass (Simmonds and MacLennan 2008; Boswell et al. 2010; Egerton et al. 2018) — within the range that can be reasonably attributable to fishes in the Aransas Channel Inlet, Texas. By considering these effects in the context of seasonal variation in species composition, we can make inferences on the ecological role that channel inlet habitat plays for fishes in the Texas Coastal Bend region. With this knowledge, it is also possible to make inferences on the impact that ship traffic, maintenance activities, and the significant development plans for the Aransas Channel Inlet and adjacent land (summarized in Chenevert et al. 2019; TCEQ proposal WQ0005253000; USEPA proposal TX0138347; USACE proposal SWG-2019-00067; USACE proposal SWG-2019-00245) might have under different conditions.

Temperature is known to affect the distribution of estuarine and coastal species in the GOM (e.g., Dance and Rooker

Fig. 4 Proportional abundance of common species in the Texas Parks and Wildlife Department bag seine survey. Proportions were calculated based on the mean abundance of each species across sampling trips in each season

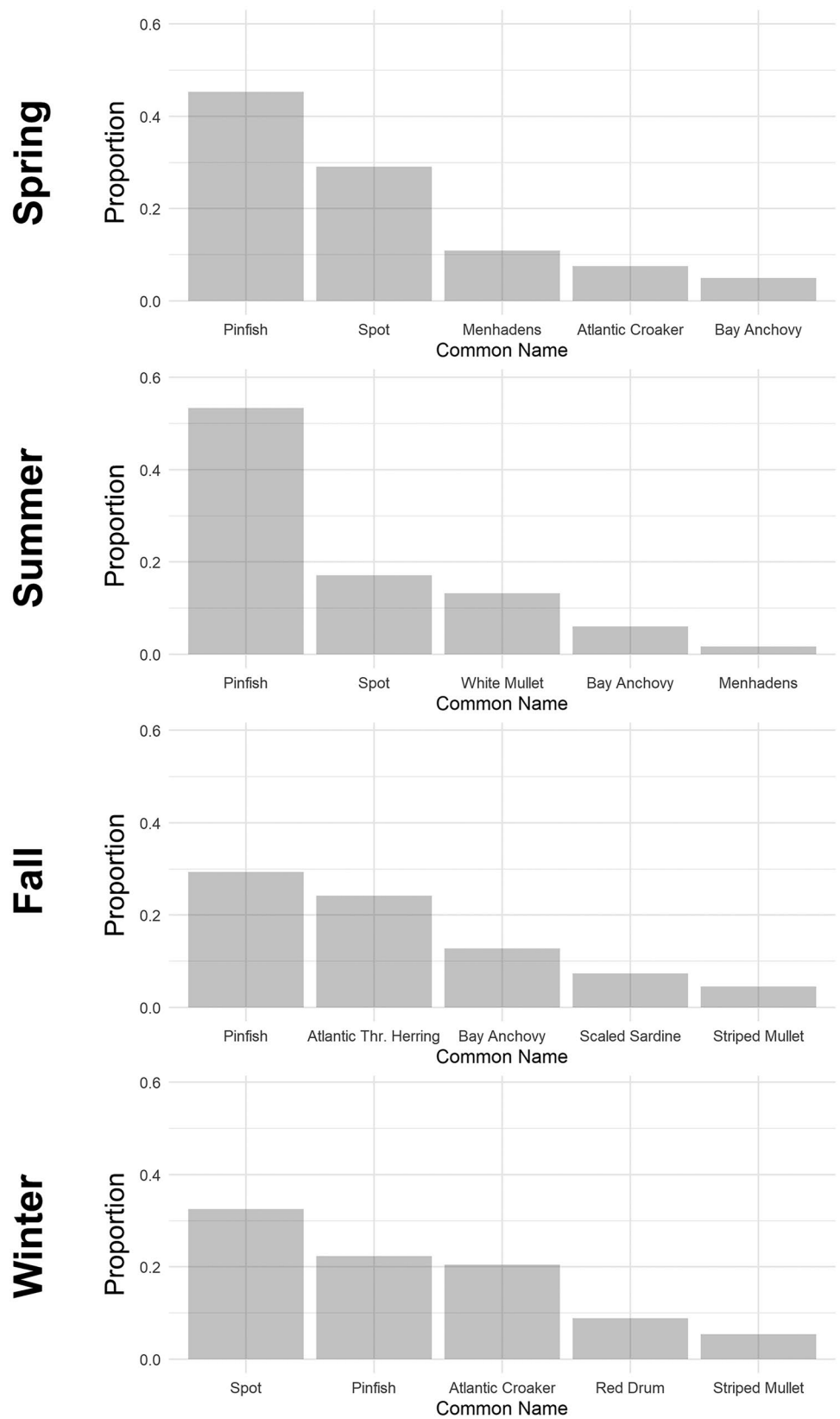
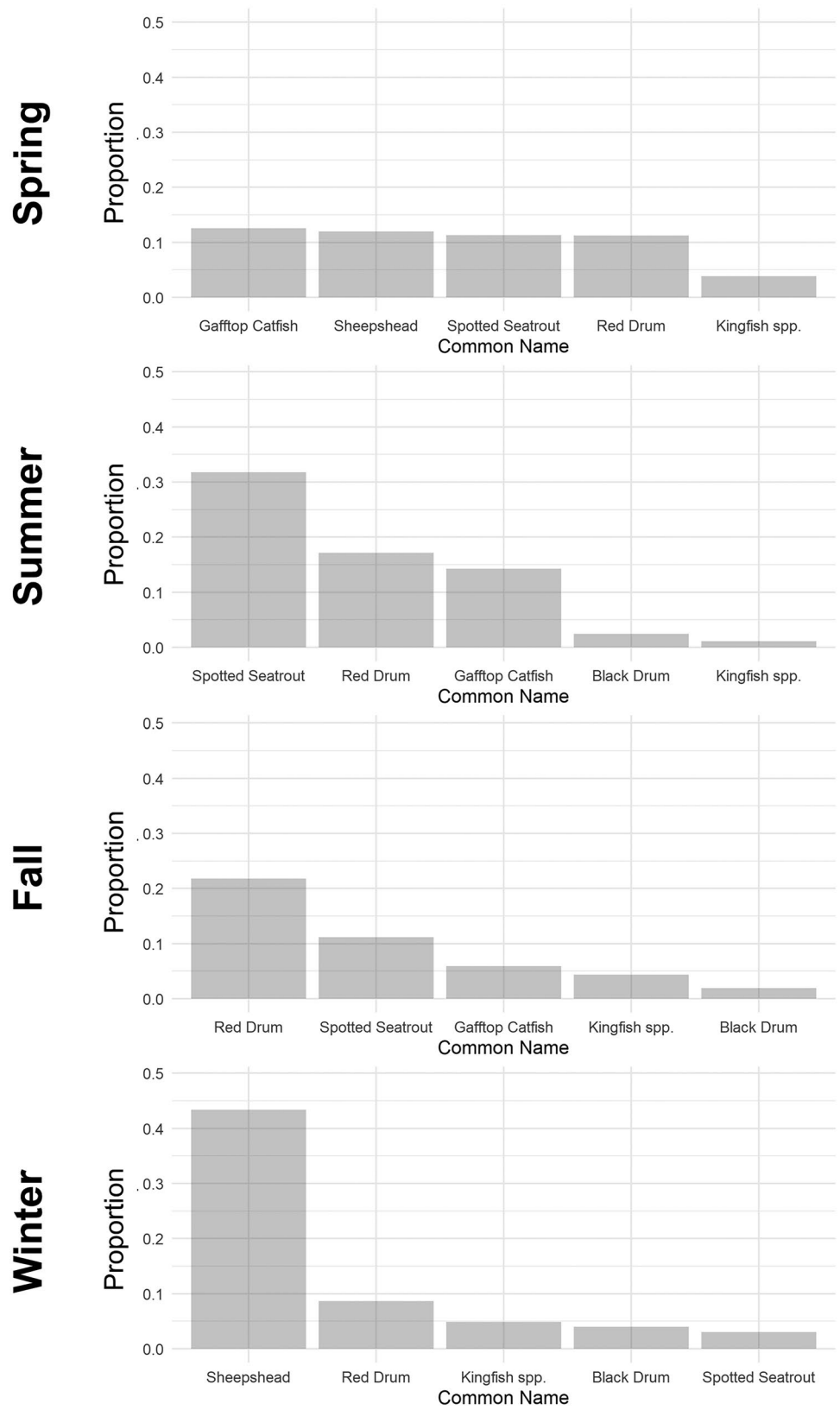


Fig. 5 Proportional abundance of common species in the fishery-dependent data collected at Robert's Point public fish cleaning facility. Proportions were calculated based on the median abundance of each species across sampling trips in each season



2015) and has been suggested to determine large-scale fish distribution (Pörtner 2001; Perry et al. 2005; but see Jutfelt et al. 2018 and references therein). In the Aransas Channel Inlet, temperature was the most important predictor of variation in fish acoustic backscatter and had a positive effect at low and high extremes, while its effect was negative at moderate levels (Fig. 3). We believe there are two dimensions to the effect of temperature on fish acoustic backscatter in our study system. The first could be associated with seasonal shifts in species composition within the region (Figs. 3 and 4). In the summer and fall months when water temperatures are high, pelagic species (e.g., Bay Anchovy, Menhaden, White Mullet) are among the most common species sampled in the TPWD bag seine survey (~ 21% and 49% of catch on average for summer and fall, respectively; Fig. 3). By contrast, the relative abundance of pelagic species was lower in the spring (~ 16%) and winter (~ 5%) (Fig. 4). Since the pelagic habitat these fishes occupy is well sampled by acoustics and they often form large, dense schools when encountered, we believe that their presence has a role in explaining why the effect of temperature on acoustic backscatter is positive at high temperatures.

The second dimension of the effect of temperature on fish acoustic backscatter is associated with episodic frontal systems and requires an understanding of another term in our model to interpret: change in barometric pressure. High pressure systems in the GOM Coast are relatively common in the winter months and are associated with rapid drops in temperature, high sustained and gusting winds, and increases in barometric pressure (Henry 1979; Mossa and Roberts 1990; Bevington et al. 2017). Low pressure systems, such as tropical storms and hurricanes, are less common but are highly impactful when they occur (Conner et al. 1989; Greening et al. 2006; Hogan et al. 2020). There is a strong body of literature that documents the effects of low-pressure systems on the movement, behavior, and distribution of fishes (e.g., Heupel et al. 2003; Massie et al. 2020; Strickland et al. 2020a, b) and other animals (e.g., Metcalfe et al. 2013; Pellegrino et al. 2013; Strickland et al. 2020a, b), indicating that fishes and other animals are capable of sensing and responding to changes in barometric pressure. Similar to previous studies, we observed that falling barometric pressure had a positive effect on fish acoustic backscatter (Fig. 3), although the increases in barometric pressure documented in this study were not associated with extreme low-pressure systems of the same destructive magnitude as prior work (e.g., Tropical Cyclones, Massie et al. 2020). However, we also documented that positive changes in barometric pressure influence fishes (Fig. 3). Increases in barometric pressure, as occur in cold fronts during the winter months, had a positive effect on fish acoustic backscatter (Fig. 3). Since barometric pressure does not have a plausible deleterious effect on fish physiology at the levels

we detected, we pose that it serves as a signal that precedes forces that do exert effects on fish physiology and distribution (e.g., physical disturbances, rapid changes in temperature) in this system. Accordingly, the effect of rising barometric pressure on fish acoustic backscatter likely reflects the ultimate effects of impending physical disturbances and rapid changes in temperature associated with high pressure systems in the winter. Since pelagic species that are well sampled by acoustics are not typically as common during the winter as they are in other months (Fig. 4), we pose that high biomass of fishes in general in the Aransas Channel Inlet during cold fronts explains the effects we observed.

We believe that the exceptional depth of the Aransas Channel Inlet relative to nearby areas has a role in explaining why changes in barometric pressure and low temperatures had positive effects on fish acoustic backscatter (Fig. 3). A strong body of literature documents that frontal systems have been associated with the movements of fishes and other aquatic animals to deeper waters (e.g., Jury et al. 1995; Heupel et al. 2003; Bacheler et al. 2019). The Aransas Channel Inlet connects six bay systems to the GOM, including Aransas, Corpus Christi, and Redfish bays, where fishery-independent sampling was conducted (Fig. 1). These six bays have mean depths of 0.7–3.6 m (Ward 1997), while the depth of the Aransas Channel Inlet was generally 15–18 m at the time of the study. The substantial volume of water in the relatively small geographic area that the Aransas Channel Inlet covers is likely to change temperature less rapidly than the shallow waters of the bay system. While differences in temperature between the Aransas Channel Inlet and bay system are likely to be relatively small in magnitude due to the well-mixed nature of waters and high flow rates in the Aransas Channel Inlet (Williams et al. 1991; Ward 1997; Brown et al. 2000), they may be biologically relevant at the edges of thermal tolerance for some species. Thus, our results suggest that the effect of barometric pressure change on fishes to be particularly impactful when temperatures are already cold before a cold front affects the area, illustrating the second dimension of the effect of temperature on fish acoustic backscatter.

The jetties that line the Aransas Channel Inlet and its deep depth are likely to protect fishes and other organisms from the physical disturbances they would experience due to high wind and wave action during cold fronts in the shallower bays. Indeed, prior studies have documented associations between physical disturbances from frontal systems and movement of aquatic animals into deeper waters (Roberts and Sauer 1994; Bacheler et al. 2019). The knowledge that fishes seek deeper waters in response to episodic frontal systems is not restricted to the scientific community; while not conducted formally, our conversations with local fishing guides indicated that the fishing community has long been aware that gamefishes are found

in higher concentrations in channels and other deep areas during cold fronts. In such times and when other frontal systems occur, we pose that the Aransas Channel Inlet and deep channels lined with jetties like it may serve as refuge habitat for fishes against episodic environmental and physical disturbances. Alternatively, the Aransas Channel Inlet could simply be acting as a conduit for movement out of the bay system into the coastal ocean in response to frontal systems.

Salinity in the study region is similar to temperature in that it varies seasonally (Applebaum et al. 2005). The effect of salinity on fish acoustic backscatter was positive at low salinities and slightly negative at moderate and high salinities (Fig. 3). This could suggest that movement into the Aransas Channel Inlet could buffer fishes from the effects of freshwater inflow events — similar to its role as a refuge against cold fronts — although the salinities we measured in this study were unlikely to be physiologically stressful for most species in the region. While salinity was not correlated with barometric difference or temperature at a level that precluded its inclusion in our models, the effect of salinity is unlikely to be completely independent of those variables. Cold fronts in the winter are typically associated with precipitation, and since the positive effect of salinity is associated with relatively few data points (Fig. 3), it is possible that rainfall during winter cold fronts could explain the positive effect of salinity on fish acoustic backscatter at low salinities. Indeed, prior studies found that increased runoff during episodic frontal systems was associated with down-estuary movements of aquatic animals (Jury et al. 1995; Bailey and Secor 2016). Despite being retained in our final model, salinity was less important than temperature or change in barometric pressure in explaining variability in fish acoustic backscatter in the Aransas Channel Inlet (Fig. 3).

The potential for the Aransas Channel Inlet to act as a refuge habitat against episodic environmental and physical disturbances is somewhat paradoxical in the context of the heavy ship traffic and recreational fishing pressure in the area — both of which are likely to disturb fishes. Providing a refuge habitat for fishes, conduit for fish movement, or area for fish to spawn was almost certainly not a goal when the Aransas Channel Inlet was dredged and fortified in 1919, yet it likely serves these crucial ecological roles now. Our findings add to a growing body of literature that documents important ecological roles and abundant fish communities at industrialized, human-made structures such as petroleum platforms (Gallaway and Lewbel 1982; Claisse et al. 2014; Bolser et al. 2021), dock pilings (Brandl et al. 2017), and wind farms (Stenberg et al. 2015; Methratta and Dardick 2019; Glarou et al. 2020). Despite the disturbances that are associated with industrial activities in these areas, and the harm that their construction and operation is associated

with at times, they should be viewed as legitimate habitat for fishes and other marine life and managed accordingly. In case of the Aransas Channel Inlet, the deep, fortified channel provides a habitat that is distinct from others in the area, and accordingly may provide unique benefits that increase the resiliency of fish communities in the region.

There were several important assumptions we made when interpreting our results that should be verified with future studies. First, we assumed that increases in fish acoustic backscatter were the result of fishes moving from other areas into the Aransas Channel Inlet. It is also possible that increases in fish acoustic backscatter were due to resident fishes moving into the water column and away from the rocky jetties, as demersal and closely structure-associated species are not well-sampled by acoustics. Telemetry or other types of tagging studies (e.g., Ajemian et al. 2018) could be used to test this assumption. The second major assumption we made was that our fishery-independent and dependent datasets were representative of species compositions in the Aransas Channel Inlet. Our expertise in the region and conversations with fishers and other scientists suggest that this assumption was largely reasonable. However, there were notable trends in species composition within the channel inlet that we were aware of that may not have been captured by our data. The most notable of these was the influx of large, adult Red Drum into the channel inlet that occurs in the fall months when spawning aggregations are formed (Holt 2008; Lowerre-Barbieri et al. 2008). This phenomenon has been well documented in both the popular (e.g., Young 2007; Richard 2016; Leschper 2020) and scientific (Holt 2008) literature in the study area. The fishery is predominantly catch and release as spawners are typically larger than the slot limit of 20–28 inches, although Red Drum relative abundance in the fishery-dependent data peaked during the spawning season despite this (Fig. 5). This is likely because fishers in Texas are granted a tag to harvest an over-slot Red Drum and fish within the slot limit can be caught alongside large adults. So, while Red Drum relative abundance peaked during their spawning season, it is unlikely that the fishery-dependent data completely reflected the relative abundance of Red Drum during this period. The influx of large Red Drum had an uncertain effect on our acoustic data, as while Red Drum are a demersal species that may not be well-sampled by acoustics, large spawning or pre-spawning aggregations occur close enough to the surface to be recorded by aerial surveys (Lowerre-Barbieri et al. 2016). Similar to Red Drum, Sheepshead also form large spawning and pre-spawning aggregations in the Aransas Channel Inlet that fishers target heavily. Sheepshead are primarily demersal or reef-associated but have similarly been observed to form pelagic spawning or pre-spawning aggregations (Heyman et al. 2017, 2019; Grüss et al. 2018a, b), and the increase in Sheepshead relative abundance during the spawning and

pre-spawning period appeared to have been captured well by the fishery-dependent data (Fig. 5). The representativeness of our fishery-independent and dependent datasets, and the degree to which Red Drum, Sheepshead, and other common species were present in our acoustic data, could be verified with direct capture approaches such as midwater and bottom trawling, gillnetting, or hook-and-line sampling conducted directly in the channel. Finally, another important assumption that we made was that the thresholds on acoustic data effectively ensured that recorded backscatter was attributable to fishes. While reasonable based on prior studies (Boswell et al. 2007; Simmonds and MacLennan 2008; Rudstam et al. 2009) and our knowledge of the ecosystem, it is possible that dense groups of small, non-fish scattering sources could have reflected acoustic energy that exceeded the thresholds we employed. Our assumption that backscatter recorded in this study was primarily attributable to fishes could also be verified with direct capture approaches such as trawling.

Significant development activities are planned for the Aransas Channel Inlet and adjacent land, including channel deepening, widening, and installation of a desalination plant and VLCC terminal (summarized in Chenevert et al. 2019; TCEQ proposal WQ0005253000; USEPA proposal TX0138347; USACE proposal SWG-2019-00067; USACE proposal SWG-2019-00245). Considering the effects we described and the suspected role of the Aransas Channel Inlet as an important refuge habitat, and with the assumptions made in this study in mind, we can make inferences on the impact of development, maintenance activities, or shipping activities in the Aransas Channel Inlet under different conditions. Our data suggest that proposed development activities, maintenance, and ship traffic will be least impactful to non-demersal fishes when temperatures and salinities are moderate (c.a. 20–26 °C and 27–32 psu; Fig. 3), and frontal systems are not expected to impact the area (barometric pressure change of c.a. –6–2 mb over 24 h; Fig. 3). Conversely, development and maintenance activities would be most impactful if conducted when temperatures are cold (< c.a. 15 °C; Fig. 3), salinities are low (< c.a. 25 psu; Fig. 3), and a frontal system has affected the area (barometric pressure increase < c.a. 3 mb or decrease > 7 mb over 24 h; Fig. 3), or when temperatures are at their highest (> c.a. 28 °C; Fig. 3). Similarly, the use of this channel inlet by such fishes during these cold, low salinity frontal systems suggests that shipping traffic during these events could also be impactful — particularly where VLCCs, which draft ~20–30 m, are concerned. Additional work is certainly warranted to assess the specifics and extent of such impacts for this area. Since the Aransas Channel Inlet provides a unique type of habitat and is the only connection between coastal and estuarine habitats for tens of kilometers, we believe that care taken — or not taken — to minimize the impact such activities to fishes in this relatively small area could have disproportionate impacts on the fish populations of the wider region.

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Data Availability Data are available upon request.

References

- Ajemian, M.J., K.S. Mendenhall, J.B. Pollack, M.S. Wetz, and G.W. Stunz. 2018. Moving Forward in a Reverse Estuary: Habitat Use and Movement Patterns of Black Drum (*Pogonias cromis*) Under Distinct Hydrological Regimes. *Estuaries and Coasts* 41: 1410–1421. <https://doi.org/10.1007/s12237-017-0363-6>.
- Allen, R.M., A. Metaxas, and P.V.R. Snelgrove. 2018. Applying Movement Ecology to Marine Animals with Complex Life Cycles. *Annual Review of Marine Science* 10: 19–42. <https://doi.org/10.1146/annurev-marine-121916-063134>.
- Applebaum, S., P.A. Montagna, and C. Ritter. 2005. Status and Trends of Dissolved Oxygen in Corpus Christi Bay, Texas, U.S.A. *Environmental Monitoring and Assessment* 107: 297–311. <https://doi.org/10.1007/s10661-005-3111-5>.
- Bacheler, N.M., K.W. Shertzer, R.T. Cheshire, and J.H. MacMahan. 2019. Tropical storms influence the movement behavior of a demersal oceanic fish species. *Scientific Reports* 9. Nature Publishing Group: 1481. <https://doi.org/10.1038/s41598-018-37527-1>.
- Bailey, H., and D.H. Secor. 2016. Coastal evacuations by fish during extreme weather events. *Scientific Reports* 6. Nature Publishing Group: 30280. <https://doi.org/10.1038/srep30280>.
- Barkan, R., J.C. McWilliams, A.F. Shchepetkin, M.J. Molemaker, L. Renault, A. Bracco, and J. Choi. 2017. Submesoscale Dynamics in the Northern Gulf of Mexico. Part I: Regional and Seasonal Characterization and the Role of River Outflow. *Journal of Physical Oceanography* 47. American Meteorological Society: 2325–2346. <https://doi.org/10.1175/JPO-D-17-0035.1>.
- Baumann, H., and E.M. Smith. 2018. Quantifying Metabolically Driven pH and Oxygen Fluctuations in US Nearshore Habitats at Diel to Interannual Time Scales. *Estuaries and Coasts* 41: 1102–1117. <https://doi.org/10.1007/s12237-017-0321-3>.
- Bevington, A.E., R.R. Twilley, C.E. Sasser, and G.O. Holm. 2017. Contribution of river floods, hurricanes, and cold fronts to elevation change in a deltaic floodplain, northern Gulf of Mexico, USA. *Estuarine, Coastal and Shelf Science* 191: 188–200. <https://doi.org/10.1016/j.ecss.2017.04.010>.
- Bianchi, T.S., J.R. Pennock, and R.R. Twilley. 1998. *Biogeochemistry of Gulf of Mexico Estuaries*. John Wiley & Sons.

- Bolser, D.G., J.P. Egerton, A. Grüss, T. Loughran, T. Beyea, K. McCain, and B.E. Erisman. 2020. Environmental and Structural Drivers of Fish Distributions among Petroleum Platforms across the U.S. Gulf of Mexico. *Marine and Coastal Fisheries* 12: 142–163. <https://doi.org/10.1002/mcf2.10116>.
- Bolser, D.G., P. Jack, A. Grüss, Egerton, and B.E. Erisman. 2021. Optic-acoustic Analysis of Fish Assemblages at Petroleum Platforms. *Fisheries* 46: 552–563. <https://doi.org/10.1002/fsh.10654>.
- Boswell, K.M., R.J.D. Wells Jr., James H. Cowan, and C.A. Wilson. 2010. Biomass, Density, and Size Distributions of Fishes Associated with a Large-Scale Artificial Reef Complex in the Gulf of Mexico. *Bulletin of Marine Science* 86: 879–889. <https://doi.org/10.5343/bms.2010.1026>.
- Boswell, K.M., M.P. Wilson, and C.A. Wilson. 2007. Hydroacoustics as a tool for assessing fish biomass and size distribution associated with discrete shallow water estuarine habitats in Louisiana. *Estuaries and Coasts* 30: 607–617. <https://doi.org/10.1007/BF02841958>.
- Brandl, S.J., J.M. Casey, N. Knowlton, and J.E. Duffy. 2017. Marine dock pilings foster diverse, native cryptobenthic fish assemblages across bioregions. *Ecology and Evolution* 7: 7069–7079. <https://doi.org/10.1002/ece3.3288>.
- Breitburg, D.L. 1992. Episodic Hypoxia in Chesapeake Bay: Interacting Effects of Recruitment, Behavior, and Physical Disturbance. *Ecological Monographs* 62: 525–546. <https://doi.org/10.2307/2937315>.
- Brown, C.A., S.A. Holt, G.A. Jackson, D.A. Brooks, and G.J. Holt. 2004. Simulating larval supply to estuarine nursery areas: How important are physical processes to the supply of larvae to the Aransas Pass Inlet? *Fisheries Oceanography* 13: 181–196. <https://doi.org/10.1111/j.1365-2419.2004.00285.x>.
- Brown, Cheryl A., G.A. Jackson, and D.A. Brooks. 2000. Particle transport through a narrow tidal inlet due to tidal forcing and implications for larval transport. *Journal of Geophysical Research: Oceans* 105: 24141–24156. <https://doi.org/10.1029/2000JC000211>.
- Callihan, J.L., J.H. Cowan, and M.D. Harbison. 2015. Sex-Specific Movement Response of an Estuarine Sciaenid (*Cynoscion nebulosus*) to Freshets. *Estuaries and Coasts* 38: 1492–1504. <https://doi.org/10.1007/s12237-014-9889-z>.
- Chenevert, C., J. Hodder, E. Fucile, and J. Blackburn. 2019. Texas Coastal Bend Industrial Development Harbor Island Information Booklet. Available: <https://img1.wsimg.com/blobby/go/c43bc452-5b67-4b56-8dd1-774f844a33c1/downloads/Texas%20Coastal%20Bend%20Development%20D2%20.pdf?ver=1570640620717>.
- Ciannelli, L., P. Fauchald, K.S. Chan, V.N. Agostini, and G.E. Dingsør. 2008. Spatial fisheries ecology: Recent progress and future prospects. *Journal of Marine Systems* 71. The Wrapping Up of the IDEA Project: 223–236. <https://doi.org/10.1016/j.jmarsys.2007.02.031>.
- Claisse, J.T., D.J. Pondella, M. Love, L.A. Zahn, C.M. Williams, J.P. Williams, and A.S. Bull. 2014. Oil platforms off California are among the most productive marine fish habitats globally. *Proceedings of the National Academy of Sciences* 111. Proceedings of the National Academy of Sciences: 15462–15467. <https://doi.org/10.1073/pnas.1411477111>.
- Conner, W.H., J.W. Day, R.H. Baumann, and J.M. Randall. 1989. Influence of hurricanes on coastal ecosystems along the northern Gulf of Mexico. *Wetlands Ecology and Management* 1: 45–56. <https://doi.org/10.1007/BF00177889>.
- Cushing, D.H. 1982. *Fisheries Biology: A Study in Population Dynamics*, 2nd ed., 295. Madison, Wisconsin, USA: University of Wisconsin Press.
- Dance, M.A., and J.R. Rooker. 2015. Habitat- and bay-scale connectivity of sympatric fishes in an estuarine nursery. *Estuarine, Coastal and Shelf Science* 167: 447–457. <https://doi.org/10.1016/j.ecss.2015.10.025>.
- Demer, D.A., L. Berger, M. Bernasconi, E. Bethke, K. Boswell, D. Chu, R. Domokos, et al. 2015. *Calibration of acoustic instruments*. Report. International Council for the Exploration of the Sea (ICES). <https://doi.org/10.25607/OBP-185>.
- Egerton, J.P., A.F. Johnson, J. Turner, L. LeVay, I. Mascareñas-Osorio, and O. Aburto-Oropeza. 2018. Hydroacoustics as a tool to examine the effects of Marine Protected Areas and habitat type on marine fish communities. *Scientific Reports* 8. Nature Publishing Group: 47. <https://doi.org/10.1038/s41598-017-18353-3>.
- Egerton, Jack P., D.G. Bolser, A. Grüss, and B.E. Erisman. 2021. Understanding patterns of fish backscatter, size and density around petroleum platforms of the U.S. Gulf of Mexico using hydroacoustic data. *Fisheries Research* 233: 105752. <https://doi.org/10.1016/j.fishres.2020.105752>.
- Flint, R.W. 1985. Long-term estuarine variability and associated biological response. *Estuaries* 8: 158–169. <https://doi.org/10.2307/1351865>.
- Fuiman, L.A. 2018. Egg boon fatty acids reveal effects of a climatic event on a marine food web. *Ecological Monographs* 88: 585–599. <https://doi.org/10.1002/ecm.1324>.
- Gallaway, B.J., and G.S. Lewbel. 1982. *The Ecology of Petroleum Platforms in the Northwestern Gulf of Mexico: A Community Profile*. U.S. Department of the Interior, Bureau of Land Management, Fish and Wildlife Service.
- Glarou, M., M. Zrust, and J.C. Svendsen. 2020. Using Artificial-Reef Knowledge to Enhance the Ecological Function of Offshore Wind Turbine Foundations: Implications for Fish Abundance and Diversity. *Journal of Marine Science and Engineering* 8. Multidisciplinary Digital Publishing Institute: 332. <https://doi.org/10.3390/jmse8050332>.
- Greening, H., P. Doering, and C. Corbett. 2006. Hurricane Impacts on Coastal Ecosystems. *Estuaries and Coasts* 29. Coastal and Estuarine Research Federation: 877–879.
- Grüss, A., C. Biggs, W.D. Heyman, and B. Erisman. 2018a. Prioritizing monitoring and conservation efforts for fish spawning aggregations in the U.S. Gulf of Mexico. *Scientific Reports* 8. Nature Publishing Group: 8473. <https://doi.org/10.1038/s41598-018-26898-0>.
- Grüss, A., D.D. Chagaris, E.A. Babcock, and J.H. Tarnecki. 2018b. Assisting Ecosystem-Based Fisheries Management Efforts Using a Comprehensive Survey Database, a Large Environmental Database, and Generalized Additive Models. *Marine and Coastal Fisheries* 10: 40–70. <https://doi.org/10.1002/mcf2.10002>.
- Grüss, A., M.D. Drexler, E. Chancellor, C.H. Ainsworth, J.S. Gleason, J.M. Tirpak, M.S. Love, and E.A. Babcock. 2019. Representing species distributions in spatially-explicit ecosystem models from presence-only data. *Fisheries Research* 210: 89–105. <https://doi.org/10.1016/j.fishres.2018.10.011>.
- Grüss, A., J.L. Pirtle, J.T. Thorson, M.R. Lindeberg, A.D. Neff, S.G. Lewis, and T.E. Essington. 2021. Modeling nearshore fish habitats using Alaska as a regional case study. *Fisheries Research* 238: 105905. <https://doi.org/10.1016/j.fishres.2021.105905>.
- Grüss, A., K.A. Rose, D. Justić, and L. Wang. 2020. Making the most of available monitoring data: A grid-summarization method to allow for the combined use of monitoring data collected at random and fixed sampling stations. *Fisheries Research* 229: 105623. <https://doi.org/10.1016/j.fishres.2020.105623>.
- Harden Jones, F.R. 1968. *Fish Migration*. Edward Arnold, London, UK. 325 pp.
- Hartig, F. 2021. DHARMA: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.1. <https://CRAN.R-project.org/package=DHARMA>.
- Henry, W.K. 1979. Some Aspects of the Fate of Cold Fronts in the Gulf of Mexico. *Monthly Weather Review* 107. American Meteorological Society: 1078–1082. https://journals.ametsoc.org/view/journals/mwre/107/8/1520-0493_1979_107_1078_saotfo_2_0_co_2.xml?tab_body=fulltext-display.
- Heupel, M.R., C.A. Simpfendorfer, and R.E. Hueter. 2003. Running before the storm: Blacktip sharks respond to falling barometric pressure associated with Tropical Storm Gabrielle. *Journal of Fish Biology* 63: 1357–1363. <https://doi.org/10.1046/j.1095-8649.2003.00250.x>.

- Heyman, W.D., A. Grüss, C.R. Biggs, S. Kobara, N.A. Farmer, M. Karnauskas, S. Lowerre-Barbieri, and B. Erisman. 2019. Cooperative monitoring, assessment, and management of fish spawning aggregations and associated fisheries in the U.S. Gulf of Mexico. *Marine Policy* 109: 103689. <https://doi.org/10.1016/j.marpol.2019.103689>.
- Heyman, W., K. McCain, T.J. Rowell, B. Erisman, and B. Gallaway. 2017. Initial Documentation of a Multi-Species Spawning Aggregation in Galveston TX, with a Focus on Sheepshead, *Archosargus probatocephalus*. In . AFS.
- Hogan, J.A., R.A. Feagin, G. Starr, M. Ross, T.-C. Lin, C. O'connell, T.P. Huff, et al. 2020. A Research Framework to Integrate Cross-Ecosystem Responses to Tropical Cyclones. *BioScience* 70: 477–489. <https://doi.org/10.1093/biosci/biaa034>.
- Holt, S.A. 2008. Distribution of Red Drum Spawning Sites Identified by a Towed Hydrophone Array. *Transactions of the American Fisheries Society* 137: 551–561. <https://doi.org/10.1577/T03-209.1>.
- Holt, S.A., C.L. Kitting, and C.R. Arnold. 1983. Distribution of Young Red Drums among Different Sea-Grass Meadows. *Transactions of the American Fisheries Society* 112: 267–271. <https://afspubs.onlinelibrary.wiley.com/doi/abs/10.1577/1548-8659%281983%29112%3C267%3ADOYRDA%3E2.0.CO%3B2>.
- Jury, S.H., W.H. Howell, and Watson, and W. H. Iii. 1995. Lobster movements in response to a hurricane. *Marine Ecology Progress Series* 119: 305–310. <https://doi.org/10.3354/meps119305>.
- Jutfelt, F., T. Norin, R. Ern, J. Overgaard, T. Wang, D.J. McKenzie, S. Lefevre, et al. 2018. Oxygen- and capacity-limited thermal tolerance: blurring ecology and physiology. *Journal of Experimental Biology* 221: jeb169615. <https://doi.org/10.1242/jeb.169615>.
- Leathwick, J.R., J. Elith, and T. Hastie. 2006. Comparative performance of generalized additive models and multivariate adaptive regression splines for statistical modelling of species distributions. *Ecological Modelling* 199: Predicting Species Distributions: 188–196. <https://doi.org/10.1016/j.ecolmodel.2006.05.022>.
- Leschper, W. 2020. Texas fishing calendar: In October head to Gulf beaches for redfish. *The Texas Outdoor Digest*.
- Lin, J., C. Li, K.M. Boswell, M. Kimball, and L. Rozas. 2016. Examination of Winter Circulation in a Northern Gulf of Mexico Estuary. *Estuaries and Coasts* 39: 879–899. <https://doi.org/10.1007/s12237-015-0048-y>.
- Lowerre-Barbieri, S.K., L.R. Barbieri, J.R. Flanders, A.G. Woodward, C.F. Cotton, and M.K. Knowlton. 2008. Use of Passive Acoustics to Determine Red Drum Spawning in Georgia Waters. *Transactions of the American Fisheries Society* 137: 562–575. <https://doi.org/10.1577/T04-226.1>.
- Lowerre-Barbieri, S.K., C. Friess, L.P. Griffin, D. Morley, G.B. Skomal, J.W. Bickford, N. Hammerschlag, et al. 2021. Movescapes and eco-evolutionary movement strategies in marine fish: Assessing a connectivity hotspot. *Fish and Fisheries* 22: 1321–1344. <https://doi.org/10.1111/faf.12589>.
- Lowerre-Barbieri, S.K., S.L. Walters Burnsed, and J.W. Bickford. 2016. Assessing reproductive behavior important to fisheries management: A case study with red drum, *Sciaenops ocellatus*. *Ecological Applications* 26: 979–995. <https://doi.org/10.1890/15-0497>.
- Massie, J.A., B.A. Strickland, R.O. Santos, J. Hernandez, N. Viadero, R.E. Boucek, H. Willoughby, M.R. Heithaus, and J.S. Rehage. 2020. Going Downriver: Patterns and Cues in Hurricane-Driven Movements of Common Snook in a Subtropical Coastal River. *Estuaries and Coasts* 43: 1158–1173. <https://doi.org/10.1007/s12237-019-00617-y>.
- McMillan, S.K., H.F. Wilson, C.L. Tague, D.M. Hanes, S. Inamdar, D.L. Karwan, T. Loecke, J. Morrison, S.F. Murphy, and P. Vidon. 2018. Before the storm: Antecedent conditions as regulators of hydrologic and biogeochemical response to extreme climate events. *Biogeochemistry* 141: 487–501. <https://doi.org/10.1007/s10533-018-0482-6>.
- Metcalfe, J., K.L. Schmidt, W. Bezner Kerr, C.G. Guglielmo, and S.A. MacDougall-Shackleton. 2013. White-throated sparrows adjust behaviour in response to manipulations of barometric pressure and temperature. *Animal Behaviour* 86: 1285–1290. <https://doi.org/10.1016/j.anbehav.2013.09.033>.
- Methratta, E.T., and W.R. Dardick. 2019. Meta-Analysis of Finfish Abundance at Offshore Wind Farms. *Reviews in Fisheries Science & Aquaculture* 27. Taylor & Francis: 242–260. <https://doi.org/10.1080/23308249.2019.1584601>.
- Mossa, J., and H.H. Roberts. 1990. Synergism of Riverine and Winter Storm-Related Sediment Transport Processes in Louisiana's Coastal Wetlands 40. GCAGS Transactions.
- Nathan, R., W.M. Getz, E. Revilla, M. Holyoak, R. Kadmon, D. Saltz, and P.E. Smouse. 2008. A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences* 105 (49): 19052–19059.
- Ona, E., and R.B. Mitson. 1996. Acoustic sampling and signal processing near the seabed: The deadzone revisited. *ICES Journal of Marine Science* 53: 677–690. <https://doi.org/10.1006/jmsc.1996.0087>.
- Palmer, T.A., and P.A. Montagna. 2015. Impacts of droughts and low flows on estuarine water quality and benthic fauna. *Hydrobiologia* 753: 111–129. <https://doi.org/10.1007/s10750-015-2200-x>.
- Pellegrino, A.C., M.F.G.V. Peñaflor, C. Nardi, W. Bezner-Kerr, C. G. Guglielmo, J. M. S. Bento, and J. N. McNeil. 2013. Weather Forecasting by Insects: Modified Sexual Behaviour in Response to Atmospheric Pressure Changes. *PLOS ONE* 8. Public Library of Science: e75004. <https://doi.org/10.1371/journal.pone.0075004>.
- Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds. 2005. Climate Change and Distribution Shifts in Marine Fishes. *Science* 308. American Association for the Advancement of Science: 1912–1915. <https://doi.org/10.1126/science.1111322>.
- Peters, K.M., and R.H. McMichael. 1987. Early life history of the red drum, *Sciaenops ocellatus* (Pisces: Sciaenidae), in Tampa Bay, Florida. *Estuaries* 10: 92–107. <https://doi.org/10.2307/1352173>.
- Pörtner, H. 2001. Climate change and temperature-dependent biogeography: Oxygen limitation of thermal tolerance in animals. *Naturwissenschaften* 88: 137–146. <https://doi.org/10.1007/s001140100216>.
- R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>.
- Richard, J. 2016. Bull Redfish Ruckus. Texas Saltwater Fishing Magazine. Available: <https://www.texassaltwaterfishingmagazine.com/fishing/features/joe-richard/bull-redfish-ruckus>.
- Roberts, M.J., and W.H.H. Sauer. 1994. Environment: the key to understanding the South African chokka squid (*Loligo vulgaris reynaudii*) life cycle and fishery? *Antarctic Science* 6. Cambridge University Press: 249–258. <https://doi.org/10.1017/S0954102094000386>.
- Rooker, J.R., and S.A. Holt. 1997. Utilization of subtropical seagrass meadows by newly settled red drum *Sciaenops ocellatus*: Patterns of distribution and growth. *Marine Ecology Progress Series* 158: 139–149. <https://doi.org/10.3354/meps158139>.
- Rooker, J.R., G.W. Stunz, S.A. Holt, and T.J. Minello. 2010. Population connectivity of red drum in the northern Gulf of Mexico. *Marine Ecology Progress Series* 407: 187–196. <https://doi.org/10.3354/meps08605>.
- Ropicki, A., Hanselka, D., & Dudensing, R. 2016a. The Economic Impacts of Recreational Fishing in the Corpus Christi Bay System. Texas Sea Grant Report.
- Ropicki, A., Hanselka, D., & Dudensing, R. 2016b. The Economic Impacts of Recreational Fishing in the Aransas Bay System. Texas Sea Grant Report.

- Rudstam, L.G., S.L. Parker-Stetter, P.J. Sullivan, and D.M. Warner. 2009. Towards a standard operating procedure for fishery acoustic surveys in the Laurentian Great Lakes, North America. *ICES Journal of Marine Science* 66: 1391–1397. <https://doi.org/10.1093/icesjms/fsp014>.
- Santora, J.A., W.J. Sydeman, I.D. Schroeder, J.C. Field, R.R. Miller, and B.K. Wells. 2017. Persistence of trophic hotspots and relation to human impacts within an upwelling marine ecosystem. *Ecological Applications* 27: 560–574. <https://doi.org/10.1002/eap.1466>.
- Secor, D.H. 2015. *Migration Ecology of Marine Fishes*. JHU Press.
- Simmonds, J., and D.N. MacLennan. 2008. *Fisheries Acoustics: Theory and Practice*. John Wiley & Sons.
- Stenberg, C., J.G. Støttrup, M. van Deurs, C.W. Berg, G.E. Dinesen, H. Mosegaard, T.M. Grome, and S.B. Leonhard. 2015. Long-term effects of an offshore wind farm in the North Sea on fish communities. *Marine Ecology Progress Series* 528: 257–265. <https://doi.org/10.3354/meps11261>.
- Strickland, B.A., K. Gastrich, F.J. Mazzotti, J.A. Massie, V. Paz, N. Viadero, J.S. Rehage, and M.R. Heithaus. 2020a. Variation in movement behavior of alligators after a major hurricane. *Animal Biotelemetry* 8: 7. <https://doi.org/10.1186/s40317-020-00193-0>.
- Strickland, B.A., J.A. Massie, N. Viadero, R. Santos, K.R. Gastrich, V. Paz, P. O'Donnell, et al. 2020b. Movements of Juvenile Bull Sharks in Response to a Major Hurricane Within a Tropical Estuarine Nursery Area. *Estuaries and Coasts* 43: 1144–1157. <https://doi.org/10.1007/s12237-019-00600-7>.
- Thuiller, W., B. Lafourcade, and M. Araujo. 2010. Presentation manual for BIOMOD. *Thuiller W, Lafourcade B, Engler R, Araújo MB (2009) BIOMOD-a platform for ensemble forecasting of species distributions. Ecography* 32: 369–373.
- Ward, G.H. 1997. *Processes and trends of circulation within the Corpus Christi Bay National Estuary Program study area*. Texas Natural Resource Conservation Commission.
- Williams, R.G., T. D. Bethem, G. W. French, and H. R. Frey. 1991. Corpus Christi Bay current prediction quality assurance miniproject, NOAA Tech.Memo. NOS OMA 60, Natl. Oceanic and Atmos. Admin., Rockville, Md.
- Winner, B.L., K.E. Flaherty-Walia, T.S. Switzer, and J.L. Vecchio. 2014. Multidecadal Evidence of Recovery of Nearshore Red Drum Stocks off West-Central Florida and Connectivity with Inshore Nurseries. *North American Journal of Fisheries Management* 34. Taylor & Francis: 780–794. <https://doi.org/10.1080/02755947.2014.920737>.
- Wood, S.N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (b)* 73 (1): 3–36.
- Young, P. 2007. Bull reds are running -- let 'em go. Port Aransas South Jetty. Available: <https://www.portasouthjetty.com/articles/bull-reds-are-running-let-em-go/>.