**Spatial and temporal analyses of Atlantic common bottlenose dolphin (*Tursiops truncatus*) vocalizations and distribution patterns in Charleston Harbor, South Carolina**

Caroline Tribble1,2, Brian Balmer1,5, Melissa Hughes1,6, Patricia Fair1,3,4, Eric Montie1,2

1Graduate Program in Marine Biology, College of Charleston, Charleston, SC, USA

2Department of Natural Sciences, University of South Carolina Beaufort, Bluffton, SC, USA 3South Carolina Aquarium, Charleston, SC, USA

4Medical University of South Carolina, Charleston, SC, USA

5US Fish and Wildlife, Clancy, Montana, USA

6Department of Biology, College of Charleston, Charleston, SC, USA

**ABSTRACT**

Common bottlenose dolphins (*Tursiops truncatus*) rely on a range of vocalizations for social interactions, navigating complex environments, and acquisition of prey. However, there is increasing evidence that anthropogenic noise may alter acoustic behavior. Long-term passive acoustic monitoring (PAM) of dolphin vocalizations coupled with photo-ID visual surveys in the May River estuary, South Carolina identified dolphin sighting abundance peaks in late summer, whereas vocalizations peaked in the winter. The Charleston Harbor, similar in salt marsh habitat to the May, is a deep inlet that experiences high vessel traffic. Spatial analyses of historical Charleston photo-ID surveys identified multiple core use areas and seasonal shifts in dolphin abundance. This study utilizes PAM, visual survey, and prey abundance data collected in Charleston Harbor from December 2017 to June 2019 to determine how: i) temporal, spatial, environmental, and anthropogenic factors influence the acoustic repertoire of dolphins and ii) acoustic and visual detections correlate across space and time. Dolphin vocalizations display spatial variation in the harbor; vocalizations peaked in fall and winter following decreases in water temperature and daylight hours. Sighting abundance varied spatially with highest abundance and vocalizations at sites near the confluence of the Wando and Cooper River and at Ft Sumter at the mouth, where vessel traffic and associated noise is greater, and lowest abundance and vocalizations in the Ashley River and surprisingly the mouth of the harbor. Further investigation into the role of prey abundance, anthropogenic noise, and detection range will help in better understanding this pattern in vocalization and sighting abundance.

**INTRODUCTION**

Acoustic surveying of marine environments has shown to be an effective, indirect method for understanding the occurrence of marine mammal species over spatial and temporal scales (Rogers et al.,2013, Monczak et al. 2019). While visual survey methods (i.e., boat-based or aerial) rely on suitable weather conditions, daylight hours, and above-water animal observations to estimate abundance and distribution, a strong advantage of passive acoustic monitoring (PAM) is that it offers greater temporal resolution and data collection in adverse conditions. One constraint with PAM is that vocalization detections provide a general count of acoustic activity but differentiating individual cetaceans and extrapolating to abundance estimates have proven challenging (Marques et al. 2010; Mellinger et al. 2007; Simard et al. 2015). Additional bias can be associated with animals that are present but not vocalizing. For these reasons, PAM is used to estimate relative rather than absolute densities of animal abundance (Marques et al. 2010; Rogers et al. 2013) whereas visual surveys offer specific measures through individual counts of cetacean species (Zolman, 2002; Speakman et al. 2006; Speakman et al. 2010; Balmer et al. 2012; Waring et al. 2016; Balmer et al. 2018). The application of long-term acoustic monitoring can bolster understanding of the abundance, distribution, and behavior of cetacean species, including common bottlenose dolphins (*Tursiops truncatus*) (Castellote et al., 2015).

The Atlantic common bottlenose dolphin is a soniferous species that uses a range of vocalizations (i.e., whistles, clicks, and burst pulses) for communicating, navigating, and foraging. Whistles are omnidirectional, frequency modulated calls important in a variety of social contexts, with remarkable signal plasticity that can respond to background noise (Herzing, 1996; King and Janik, 2013; van Ginkel et al. 2017). Echolocation click trains are directional, bio-sonar signals important for navigation, prey detection, and prey capture. Burst pulses consist of a variety of pulsed signals with high repetition rate and short inter-click intervals. These signals have yet to be fully described and the functional significance of burst pulses is not well understood. For this reason, most studies on dolphin acoustic repertoire focus on whistles and echolocation bouts (Luis et al. 2016). Since acoustics play an important role in feeding events, PAM offers non-invasive approaches for understanding cetacean foraging activity (Pirotta et al. 2015; Castellote et al. 2020). Echolocation processes related to feeding have been determined with the assessment of inter-click intervals (ICI), the amount of time between clicks within an echolocation bout (Madsen and Surlykke, 2013).  Click trains of very short ICIs (less than 10 ms) have been classified as foraging buzzes, associated with attempted and/or successful prey captures (Simon et al. 2010; Nuuttila et al. 2013; Miller et al. 2004; Pirotta et al. 2015). Acevedo-Gutiérrez and Stienessen (2004) found wild bottlenose dolphins near Isla del Coco, Costa Rica, whistled at higher rates when in feeding groups versus when in non-feeding groups. PAM can provide important insight on behavioral processes associated with social and foraging vocalizations to better understand habitat use areas identified by visual surveys.

The Marine Sensory and Neurobiology Lab led by Dr. Eric Montie at University of South Carolina Beaufort (USCB) is using long-term PAM to understand the spatial and temporal rhythms of the soundscape of the May River estuary, Bluffton, South Carolina. The major biophonic contributors in this estuarine system are snapping shrimp *(Alpheus heterochaelis and A. anagulosus)*, soniferous fish (spp. belonging to family Sciaenidae), and bottlenose dolphins (*T. truncatus*). Snap rates, fish calls, and dolphin vocalizations were found in lowest abundance near the headwaters and highest towards the mouth. Fish chorusing aggregations of silver perch (*Bairdiella chrysoura*), spotted seatrout (*Cynoscion nebulosus*)*,* and red drum (*Sciaenops ocellatus*), were found to occur more frequently at the mouth, indicating this area in the May River is an important spawning ground. It has been hypothesized that increased depth, higher salinities, and higher dissolved oxygen levels at the mouth of the river promote greater secondary production and spawning aggregations (Monczak et al. 2017, 2019, and 2020). Recent studies further assessing the long-term PAM and visual monitoring of dolphins in the May River have described spatial and temporal patterns in vocalizations, dolphin abundance, and residency patterns. Marian et al. 2021 identified a significant positive correlation between the number of dolphins present and the number of vocalizations detected at the mouth. This correlation was not apparent in the winter, however, when vocalizations (predominantly echolocation) peaked and visual sightings decreased. This shift may be associated with prey movements causing resident dolphins to move towards the mouth where prey resources are greater. In addition, with overall prey abundance decreasing in the winter, it is suspected that dolphins must echolocate more and cannot rely on passive listening to detect prey during summer months when abundance is highest and spawning soniferous fish are aggregating (Marian, 2020; McCabe et al. 2010). Stomach content analyses from stranded dolphins in the waters around Charleston identified that fish species in the Family Sciaenidae were found to be a prominent portion of dolphin diet composition (Pate and McFee, 2012).

Common bottlenose dolphins are ubiquitous throughout the coastal and offshore waters of the United States (Bearzi et al. 2009). In South Carolina, the National Marine Fisheries Service (NMFS) has defined three bay, sound, and estuary (BSE) stocks (i.e., the Northern South Carolina Estuarine System Stock, the Charleston Estuarine System Stock, and the Northern Georgia/Southern South Carolina Estuarine System Stock) and two coastal stocks (i.e., the South Carolina/Georgia Coastal Stock and the Southern Migratory Coastal Stock) in which there are varying degrees of spatial overlap (Waring et al. 2016). For the Charleston Estuarine System (CES) Stock, photo-ID surveys were initiated in 1994 for a subset (Stono River Estuary and Charleston Harbor) of this stock’s boundaries and the results of this study identified three different site fidelity patterns for individual dolphins: annual residents, seasonal residents, or coastal transients (Zolman 2002). Additional photo-ID effort across extended temporal (i.e., 1994-2003) and spatial (i.e., Stono River Estuary, Charleston Harbor, Ashley River, Cooper River, Wando River, and adjacent coastal waters) scales identified 839 discrete individuals (Speakman et al. 2006). Systematic surveys were conducted from 2004-2006 to estimate abundance of the CES Stock and identified dolphin abundance to peak during the summer. This increase in abundance was attributed in part to seasonal residents and transients that were sighted in the mouth of Charleston Harbor (Speakman et al. 2010). Continued photo-ID survey effort from 2004-2009, using ArcGIS spatial analyses of sightings, identified multiple core use areas of the CES Stock (i.e., at the mouth of the harbor, near Drum Island, in the Ashley and Wando River systems) by determining kernel density estimates for dolphins sighted more than 11 times and across all seasons (Bouchillon et al. 2019). Seasonal prey abundance and distribution throughout the harbor may influence use of the core areas identified.

The Ashley, Cooper, and Wando Rivers empty into Charleston Harbor and this region has been identified as important nursery and year-round habitat for various offshore and inshore fish species, respectively (Wenner et al. 1984; SCDNR SEAMAP, 2000; Arnott, 2013). Trawling surveys conducted in the harbor have identified overall fish abundance to vary seasonally, with catch rates greatest in the summer and lowest in the winter (Arnott, 2013). Bouchillon et al. (2019) determined that dolphin distribution was highest at the entrance to Charleston Harbor during summer and fall. In contrast, dolphin distribution shifted seasonally with more individuals being sighted farther inside Charleston Harbor as well as into the Ashley and Wando Rivers during spring and winter. Seasonality in prey availability and water temperature have been predicted to be primary factors in dolphin seasonal distribution patterns (Barco, 1999; Torres et al. 2005; Toth et al. 2011). Similar to the May River, the mouth of Charleston Harbor likely supports higher secondary production, which is higher during summer and fall. In winter, dolphin diet composition may be supplied by larger, less abundant prey within the inner portions of Charleston Harbor and adjacent rivers (Bouchillon et al. 2019). Assessing the influence of soniferous fish calling activity of species known to chorus (a behavior which has been linked to fish spawning, as shown by Monczak et al. 2020) on the relationship between dolphin sightings and vocalizations, may help tease out the influence of increased fish calling and overall presence in an area.

In a highly developed estuarine ecosystem, PAM and visual survey methods together can provide a more detailed picture for understanding how vessel noise influences bottlenose dolphin behavior. From December 2017 to May 2019, continuous PAM and water quality measurements (e.g. water temperature and depth) were recorded in addition to bimonthly photo-ID surveys in six of the core use areas determined by Bouchillon et al. (2019) within Charleston Harbor and surrounding waters. The proposed study aims to conduct a multi-faceted approach using the data described above to characterize bottlenose dolphin acoustic vocalizations and visual sightings within Charleston Harbor on a spatial and temporal scale. There will be two specific goals for this study: i) Determine how well passive acoustics can serve as a predictor for dolphin abundance, and ii) Assess spatial, temporal, biological, and anthropogenic factors that may influence this relationship.

**METHODS**

***Study Area***

The Charleston Harbor (32˚40’N, 79˚55’W) is an inlet that is 3.7 km in width and 7.56 km long from the mouth of the harbor to the eastern edge of downtown Charleston proper (Fig. 1). The Ashley, Cooper, and Wando River are tributaries that empty into the Harbor, with the Wando terminal the major port of Charleston. Placement of recording stations within Charleston Harbor was determined based on core use areas of the CES Stock using kernel density estimate (KDE) analyses on photo-ID surveys conducted from 2004-2009 (Bouchillon, 2016; Bouchillon et al. 2019). Long-term PAM, environmental, and visual abundance data collection began in June 2017. Due to technical issues during the first recorder deployment and for connection to visual sighting data, the present study will focus on data collected from December 19th, 2017 to May 23rd, 2019.

***Passive Acoustic and Environmental Data Collection***

DSG-ST passive acoustic recorders were mounted within custom built instrument frames with attached water temperature (HOBO Water Temperature Pro v2 U22-001) and water level loggers (HOBO 100-Foot Depth Water Level Data Logger U20-001-02-Ti). Prior to deployments, recorders and frames are painted with anti-fouling paint to minimize damage to recorders. From December 2017 to June 2019, recorders were deployed at 6 locations in the harbor (A; Wando River, B; Drum Island, C; SC Aquarium, D; Ft Sumter, E; Ashley River, F; Citadel) set to record for 2 minutes every 20 minutes at a sampling rate of 96 kHz (Figure 1). Following each deployment, wav files are downloaded for manual analysis in Adobe Audition CS5.5 Software.

***Visual Surveys***

Small vessel-based photo-ID surveys in Charleston Harbor began in June 2017 and were conducted bimonthly within a designated 2 km radius around each recording station. Once dolphin(s) were observed, sighting data collected included GPS location, start and end times of sighting, group size estimates for dolphins, calves, and neonates (i.e., minimum, maximum, and best estimate), weather conditions, water depth (m), and water quality measurements using a YSI Handheld Multiparameter Instrument. Water quality measures included water temperature, salinity, dissolved oxygen, and turbidity. These vessel-based surveys were conducted under General Authorization for Scientific Research Letter of Confirmation No. 18859 issued by NMFS to Dr. Patricia Fair. Best estimates of group size across sightings for total dolphins and total calves will be assessed temporally (i.e. by season, year, and entire study). Photographs were taken of the dorsal fin of each group member to later use photo-ID methods (Speakman et al. 2010; Balmer et al. 2012; Balmer et al. 2018) to identify individual dolphins.

***Analysis of Acoustic Files***

Acoustic data collected from December 2017 to June 2019 in Charleston Harbor were manually analyzed on the hour using Adobe Audition CS5.5 software. Spectrograms are visualized using a spectral resolution of 2048 and a 10 s time window. In each file, bottlenose dolphin whistles, burst pulses, and echolocation bouts were identified and counted. Additionally, all biological sounds (e.g. fish calls and/or choruses, manatees, right whales), physical sounds (waves and rain), deployment artifacts (e.g. chain scrapes or knocks), and anthropogenic noise presence (e.g. vessels and dredging) were recorded.

***Data and Statistical Analysis***

Statistical analysis was performed using R software version 3.6.1. For all sightings recorded within each survey area surrounding a recording station, acoustic files recorded closest in time (within 10 minutes) of the start or end times of sightings were used to match vocalization detections with sighting abundance counts. Acoustic data included total number of vocalizations, total number of echolocation bouts, total number of burst pulses, total number of whistles, fish calling scores for the four main chorusing soniferous fish species in our estuaries (Oyster Toadfish, Silver Perch, Red Drum, and Spotted Seatrout; Monczak et al. 2019), and anthropogenic noise presence/absence (0/1 score). To account for occurrences when no dolphins were sighted in a particular site, these zeros in dolphins sighted were matched to acoustics on the hour falling within and closest to the 50-minute visual survey period. Data was then summed bimonthly (across surveys) at each survey site. For anthropogenic noise, rather than summing these data a new factor named ‘Noise Ratio’ was created which represented the percent of files with noise marked as present out of all the files assessed. To assess the influence calf presence may have on vocalization frequency, total dolphins was broken down into two new variables, ‘Adult’ and ‘Calf’. Calf was found to be insignificant in all models tested and final models were run looking at total dolphins rather than these age class specific variables. Neonate counts were not included in the total dolphin count due to the significantly lower sample size as compared to calves and adult dolphins sighted. Two photo-ID surveys (December 7th, 2017, and February 21st, 2019) were excluded from analyses due to gaps in recorder deployments when recorders were not in the water.

Generalized linear models (GLMs) were used to assess the influence of the total number of dolphins sighted on the total number of dolphin vocalizations, total echolocation bouts, total burst pulses, and total whistles in four separate generalized linear models. Model selection was based on a forward stepwise selection process and used Akaike information criterion (AIC) for model comparison. In each model, multiple factors (location/survey site, season, fish calling score sum, and noise ratio) were included to check for spatial, seasonal, environmental, and/or anthropogenic variation in vocalizations and sightings. Surveys that happen to fall on days in between deployments when the recorders were out of the water were excluded in analysis. Multiple GLMs with Gaussian, Poisson, and Negative Binomial distributions were assessed and found a Gaussian distribution with a Log+1 transformation of vocalizations fit best. To understand the importance of factors tested in the model on vocalizations, backward stepwise model selection was conducted using the stepAIC() function in R and using AIC criterion kept or removed certain factors from the model. All models displayed AICs lower by 2 points with oyster toadfish calling and noise ratio variables removed. For the models selected, likelihood-ratio chi-square tests were conducted to further understand the importance and effect size of each factor in the model. Post hoc Tukey Kramer HSD multiple comparisons of means were conducted for each selected model to define differences between group means within each of the factors included.

**RESULTS**

***Acoustic and Visual Detections***

From December 19th, 2017, to May 23rd, 2019, a total of 1,219 dolphins (including 975 adults, 240 calves, and 4 neonates) were sighted across a total of 34 photo-ID surveys. Survey effort (total time spent surveying all sites) across all surveys totaled 10,200 minutes and the overall sighting rate (total dolphins sighted / visual survey effort) was 0.120. Acoustic detections recorded within the same period (~5-10 mins of an individual sighting) of time as individual sightings, a total of 1,780 vocalizations (1,198 echolocation bouts, 361 whistles, and 221 burst pulses) were observed across 385 files matched to sightings. Acoustic survey effort (total number of files multiplied by recording time for each file) across all files analyzed totaled 770 minutes and the overall detection rate (total vocalizations detected / visual survey effort). To determine overall vocalization detection rate (DR), visual survey effort (SE) was used instead of acoustic due to file recording times being much shorter (2-minute/file) and less representative of time dolphins spent in the area.

***Modeling***

For total vocalizations, the model that fit best included a log+1 transformation of the response variable (total vocalizations), and total dolphins sighted, station, season, red drum, silver perch, and spotted seatrout calling score sums as factors (Table 1). For echolocation bouts, the model that fit best included a log+1 transformation of the response variable (total echolocation bouts), and total dolphins sighted, station, season, red drum, and silver perch calling score sums as factors (Table 1). For burst pulses, the model that fit best included a log+1 transformation of the response variable (total burst pulses), and total dolphins sighted, station, season, red drum, and spotted seatrout calling score sums as factors (Table 1). For whistles, the model that fit best included a log+1 transformation of the response variable (total whistles), and total dolphins sighted, station, and season as factors (Table 1). In addition, a site x station interaction was included as a factor in the burst pulse and whistle models. Across all models, oyster toadfish calling scores sums and noise ratio were not found to be significant variables (AIC less than 2 when these variables were removed).  Total dolphins sighted, site, and season were all found to have a significant effect on vocalizations across all models assessed (Table 2; Table 3; Figure 2).

***Spatial Patterns***

Site was determined to be a significant factor in all vocalization models tested (Table 2; Figure 3). Across the sites surveyed within Charleston Harbor, sightings at the Wando River (N = 277, SE = 0.16), SC Aquarium (N = 268, SE = 0.16), Ft Sumter (N = 236, SE = 0.14), and Drum Island (N = 209, SE = 0.12) observed the most dolphins sighted respectively, while in the lower Ashley River (N = 158, SE = 0.09) and the Citadel (N = 71, SE = 0.04) observed the least dolphins sighted (Table 4; Figure 3). Acoustic detections follow a somewhat similar pattern with the most acoustic activity in the areas surrounding the confluence of the Cooper and Wando Rivers with the harbor. Overall, the SC Aquarium (N = 905, DR = 0.53), Drum Island (N = 346, DR = 0.20), and the Wando River (N = 272, DR = 0.16) had the most dolphin vocalizations detected, while detections were lowest in the lower Ashley River (N = 102, DR = 0.06), Ft Sumter (N =82, DR = 0.05), and the Citadel (N = 73, DR = 0.04) respectively (Table 4; Figure 3). Total vocalization and echolocation bout means similarly are grouped by high and low acoustic activity across survey sites, while burst pulses were significantly higher at the SC Aquarium compared to all other sites, and whistle means only significantly differ at Drum Island and Ft Sumter (Figure 3).

***Temporal Patterns***

Season was also determined to be a significant factor in all vocalization models tested (Table 2; Table 3; Figure 4). Seasonally, sightings in the Winter (N = 468, SR = 0.17) were highest, followed by Spring (N =330, SR = 0.10), Fall (N = 278, SR = 0.12), and Summer (N = 143, SR = 0.08) months respectively (Table 5; Figure 4). Acoustic detections were highest in the Winter (N = 828, DR = 0.31) and Fall (N = 582, DR = 0.24) as compared to the Summer (N = 190, DR = 0.11), and Spring (N = 180, DR = 0.05) months respectively with significantly greater variation as compared to total dolphins sighted (Table 6; Figure 4). Total vocalization and echolocation bout means similarly display this pattern with increases in winter and fall months, while burst pulses and whistles were significantly higher during winter months (Figure 4). A closer look at seasonal trends across all six sites surveyed shows total vocalization and echolocation bout distributions in winter and fall months across sites match closest to the patterns we see overall in our sites (Figure 5; Figure 6). By contrast, burst pulses show little variation seasonally across site, except for in the winter when there is an increase at 4 sites (Ft Sumter, SC Aquarium, Drum Island, and Wando River; Figure 7). Whistles also display significant variation across sites in the winter most prominently, and spring, as compared to the summer and fall (Figure 8).

***Contribution of Fish Calling and Noise Factors***

Fish calling score sums for the main chorusing soniferous species known in the harbor (oyster toadfish, silver perch, red drum, and spotted seatrout) was shown to have little to no effect on the relationship between dolphin vocalization and sighting abundance (Table 2; Table 3). Red drum calling was the only significant fish calling factor (p = 0.035; Table 2) in the model with total vocalizations. In all models, oyster toadfish calling was found not significant to include as an explanatory variable (AIC dec > 2 when removed). Noise ratio was also found to be insignificant and was not included as a factor in any of the final models run.

**DISCUSSION**

Dolphin sightings were shown to significantly affect the total number of dolphin vocalizations present and vocalizations displayed high spatial and temporal variation. Both sighting and vocalization abundance, predominantly echolocation, was greatest near the Wando River, Drum Island, and the SC Aquarium and vocalizations peaked in abundance and variation across vocalization type (increasing in whistles and burst pulse frequency; Figures 7 and 8) during winter and fall months. This region of the harbor is heavy with commercial and recreational ship traffic, with the Wando terminal located just to the right of the Wando River recorder and on each side of the SC Aquarium the Fort Sumter ferry (left) and a shipping port for BMW unloading (right). Dolphins may need to vocalize more frequently (lombard effect) to navigate, communicate, and forage in this noisy environment and this may partially explain why we see greater vocalization density here. Behavioral shifts associated with vessel noise have been documented in multiple cetacean species. Bottlenose dolphins have been shown to alter their acoustic behavior in response to anthropogenic noise presence and other changes in ambient noise (Buckstaff, 2004; Jensen et al. 2009b; van Ginkel et al. 2017). In response to high ambient noise in Tampa Bay, Florida, bottlenose dolphins increase minimum, maximum, and peak whistle frequencies (van Ginkel et al. 2017). In Walvis Bay, Namibia, bottlenose dolphins increase some whistle frequency parameters and production rates in response to vessel presence (Gridley et al., 2016; Heiler et al. 2016). However, we also see greater abundance in dolphins sighted in these regions, suggesting noise is not the primary and/or sole factor at play influencing this relationship.

Prey abundance may also be a driving factor in spatial and temporal patterns in dolphin vocalization and sighting abundance. Across all six sites surveyed, seasonally there was not a significant difference in total dolphins sighted. However, vocalizations showed significant variation across sites seasonally, peaking in the Winter months around the Wando River, Drum Island, and the SC Aquarium most prominently for all vocalization types. In the winter months, we see a significant increase in burst pulses and whistles at the SC Aquarium site, which could be related to the decrease in prey abundance during winter months requiring dolphins to communicate and coordinate more to hunt. These spatial and temporal patterns in dolphin acoustics are similar to the findings of Bouchillon et al. 2020 of dolphins moving further into the harbor into the rivers during the winter and spring. This shift may be related to a decrease in smaller, abundant prey resources closer to the mouth of the harbor causing a foraging shift towards larger, less abundant prey items further up the inlet and river systems. Shifting foraging patterns in this way may require less energy during winter months. In addition, with the large number of container ships traveling and docking at the Wando Terminal and to the right of the SC Aquarium, dolphins may benefit from shipside feeding, where dolphins will corral fish up against the side of a container ship and may prefer these waters for feeding (Weinpress-Galipeau et al. 2021) Relating these trends to those of prey abundance in the harbor can assist in tackling this question.

Ft Sumter at the mouth of the harbor, interestingly, is the only site where dolphin vocalization and sighting abundance are in opposition, with high numbers of dolphins sighted and low vocalizations detected over time. This site being at the mouth of the harbor covers the largest area of water within the 2 Km radius the photo-ID surveys covered as compared to the other sites which have some level of overlap with land or marsh. Due to this discrepancy in the topographical features of this site as compared to the others, it is possible the acoustic recorder is missing some of vocalizations from far sightings due to the detection range of the recording system. Another possible reason we see fewer vocalizations is due to the frequency of anthropogenic noise at this site blocking signals. The Fort Sumter ferry ravels to and from Fort Sumter every hour of every day, docking only yards away from where the recorder is in the water below. Simard et al. 2015 using a passive acoustic recorder with similar hydrophone sensitivity in the Southeast USA found the detection range of bottlenose dolphin frequency-modulated whistles to be between 200 to 300 meters. Understanding our recording system detection range of dolphin vocalizations, fish calls, and anthropogenic noise in this southeast estuarine environment is a large limitation and crucial for determining the survey breadth of our passive acoustic recorder network in the harbor. Future tonal playback experiments similar to those performed by Simard could be used to start to determine our detection range. In addition, over a longer span of time sighting data within 200-300 meters of recorders may be used in conjunction with passive acoustics as done in this present study to also tease out detection range.

Another limitation with the time series ending May 23rd, 2019, there is only one summer to draw conclusions on when assessing seasonal patterns. Multiple years to assess would provide a more comprehensive assessment of these spatial and temporal patterns in vocalization and sighting abundance. When drawing conclusions on the influence of fish calling, it is important to note that most of the chorusing periods for these fish occur in the late afternoon into the night (Monczak et al. 2019). Photo-ID surveys end around 4:00 PM and because they do not necessarily overlap with chorusing periods, this may not be the best way to assess how fish calling influences this interaction. Noise ratio, which was often high likely due to these being boat-based surveys, may not be the best approach at assessing noise. Comparing long-term patterns in dolphin vocalization and sighting abundance with a reference site, the far less industrialized May River, to test whether dolphins display any acclimation to the greater anthropogenic noise exposure. Long term study of these patterns over multiple years and with incorporation of potential factors at play not assessed here (such as prey abundance) can improve and build upon these preliminary findings.

**LITERATURE CITED**

Acevedo-Gutiérrez, A., & Stienessen, S. C. (2004). Bottlenose Dolphins (*Tursiops truncatus*) Increase Number of Whistles When Feeding. *Aquatic Mammals*, *30*(3), 357–362.

Arnott, S. (2013). SCDNR Inshore Fisheries Section: five-year report to the Saltwater Recreational Fisheries Advisory Committee. 146 pp.

Barco, S. G., Swingle, W. M., Mlellan, W. A., Harris, R. N., & Pabst, D. A. (1999). Local Abundance and Distribution of Bottlenose Dolphins (*Tursiops truncatus*) in the nearshore waters of Virgina Beach, Virginia. *Marine Mammal Science*, *15*(2), 394–408.

‌

Barlett, M. L., & Wilson, G. R. (2002). Characteristics of small boat acoustic signatures. *The Journal of the Acoustical Society of America*, *112*(5), 2221–2221.

Balmer, B. C., Schwacke, L. H., Wells, R. S., Adams, J. D., Clay George, R., Lane, S. M., McLellan, W. A., Rosel, P. E., Sparks, K., Speakman, T., Zolman, E. S., & Ann Pabst, D. (2012). Comparison of abundance and habitat usage for common bottlenose dolphins between sites exposed to differential anthropogenic stressors within the estuaries of southern Georgia, U.S.A. *Marine Mammal Science*, *29*(2), E114–E135.

Balmer, B., Zolman, E., Rowles, T., Smith, C., Townsend, F., Fauquier, D., George, C., Goldstein, T., Hansen, L., Quigley, B., McFee, W., Morey, J., Rosel, P., Saliki, J., Speakman, T., & Schwacke, L. (2018). Ranging patterns, spatial overlap, and association with dolphin morbillivirus exposure in common bottlenose dolphins (Tursiops truncatus) along the Georgia, USA coast. *Ecology and Evolution*, *8*(24), 12890–12904.

Bearzi, M., Saylan, C. A., & Hwang, A. (2009). Ecology and comparison of coastal and offshore bottlenose dolphins (*Tursiops truncatus*) in California. *Marine and Freshwater Research*, *60*(6), 584.

Bouchillon, H. (2016). *Spatial Assessment of Bottlenose Dolphins (Tursiops Truncatus) in Charleston Harbor, South Carolina: Influence of Biotic and Abiotic Factors* [MSc Thesis].

Bouchillon, H., Levine, N. S., & Fair, P. A. (2019). GIS Investigation of the relationship of sex and season on the population distribution of common bottlenose dolphins (*Tursiops truncatus*) in Charleston, South Carolina. *International Journal of Geographical Information Science*, *34*(8), 1552–1566.

Buckstaff, K. C. (2004). Effects of watercraft noise on the acoustic behavior of bottlenose dolphins, *Tursiops truncatus*, in Sarasota bay, Florida. *Marine Mammal Science*, *20*(4), 709–725.

Castellote, M., Brotons, J. M., Chicote, C., Gazo, M., & Cerdà, M. (2015). Long-term acoustic monitoring of bottlenose dolphins, Tursiops truncatus, in marine protected areas in the Spanish Mediterranean Sea. *Ocean & Coastal Management*, *113*, 54–66.

Castellote, M., Thayre, B., Mahoney, M., Mondragon, J., Lammers, M. O., & Small, R. J. (2019). Anthropogenic Noise and the Endangered Cook Inlet Beluga Whale, *Delphinapterus leucas*: Acoustic Considerations for Management. *Marine Fisheries Review*, *80*(3), 63–88.

Castellote, M., Small, R., Lammers, M., Jenniges, J., Mondragon, J., Garner, C., Atkinson, S., Delevaux, J., Graham, R., & Westerholt, D. (2020). Seasonal distribution and foraging occurrence of Cook Inlet beluga whales based on passive acoustic monitoring. *Endangered Species Research*, *41*, 225–243.

Clark, C., Ellison, W., Southall, B., Hatch, L., Van Parijs, S., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuitions, analysis, and implication. *Marine Ecology Progress Series*, *395*, 201–222.

Frankel, A. S., Ellison, W. T., & Buchanan, J. (2002). Application of the Acoustic Integration Model (AIM) to predict and minimize environmental impacts. *OCEANS’02 MTS/IEEE*, *3*, 1439–1443.

Ferguson, B. G., & Cleary, J. L. (2001). In situ source level and source position estimates of biological transient signals produced by snapping shrimp in an underwater environment. *The Journal of the Acoustical Society of America*, *109*(6), 3031–3037.

Gannon, D. P., & Waples, D. M. (2004). Diets of Coastal Bottlenose Dolphins from The U.S. Mid-Atlantic Coast Differ By Habitat. *Marine Mammal Science*, *20*(3), 527–545.

Gillespie, D., Mellinger, D. K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X., & Thode, A. (2009). PAMGUARD: Semiautomated, open source software for real‐time acoustic detection and localization of cetaceans. *The Journal of the Acoustical Society of America*, *125*(4), 2547–2547.

Gridley, T., Elwen, S. H., Rashley, G., Badenas Krakauer, A., & Heiler, J. (2016). Bottlenose dolphins change their whistling characteristics in relation to vessel presence, surface behavior and group composition. *Proceedings of Meetings on Acoustics 4ENAL*, *27*(1), p. 010030. Acoustical Society of America.

‌

Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S., & Ponirakis, D. W. (2012). Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary. *Conservation Biology*, *26*(6), 983–994.

Heiler, J., Elwen, S. H., Kriesell, H. J., & Gridley, T. (2016). Changes in bottlenose dolphin whistle parameters related to vessel presence, surface behaviour and group composition. *Animal Behaviour*, *117*, 167–177.

‌

Herzing, D. L. (1996). Vocalizations and associated underwater behavior of free-ranging Atlantic spotted dolphins, *Stenella frontalis* and bottlenose dolphins *Tursiops truncatus*. *Aquatic Mammalogy.* 22(2): 61-79.

Herzing, D. (2015). Synchronous and Rhythmic Vocalizations and Correlated Underwater Behavior of Free-ranging Atlantic Spotted Dolphins (*Stenella frontalis*) and Bottlenose Dolphins (*Tursiops truncatus*) in the Bahamas. *Animal Behavior and Cognition*, *2*(1), 14–29.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer whales (Orcinus orca) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America*, *125*(1), EL27–EL32.

Jensen, F. H., Bejder, L., Wahlberg, M., & Madsen, P. T. (2009a). Biosonar adjustments to target range of echolocating bottlenose dolphins (*Tursiop*s sp.) in the wild. *Journal of Experimental Biology*, *212*(8), 1078–1086.

Jensen, F. H., Bejder, L., Wahlberg, M., Soto, N. A., Johnson, M., & Madsen, P. T. (2009b).

Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, *395*(Ross

1976), 161–175.

Jensen, F. H., Beedholm, K., Wahlberg, M., Bejder, L., & Madsen, P. T. (2012). Estimated communication range and energetic cost of bottlenose dolphin whistles in a tropical habitat. *The Journal of the Acoustical Society of America*, *131*(1), 582–592.

King, S. L., & Janik, V. M. (2013). Bottlenose dolphins can use learned vocal labels to address each other. *Proceedings of the National Academy of Sciences*, *110*(32), 13216–13221.

Kline, L. R., DeAngelis, A. I., McBride, C., Rodgers, G. G., Rowell, T. J., Smith, J., Stanley, J. A., Read, A. D., & Van Parijs, S. M. (2020). Sleuthing with sound: Understanding vessel activity in marine protected areas using passive acoustic monitoring. *Marine Policy*, *120*, 104138.

Kriesell, H. J., Elwen, S. H., Nastasi, A., & Gridley, T. (2014). Identification and Characteristics of Signature Whistles in Wild Bottlenose Dolphins (*Tursiops truncatus*) from Namibia. *PLoS ONE*, *9*(9), e106317.

Lesagev, C., Barrettime, C. S., Kingsleaynd, B. S. (1999). The effect of vessel noise on the vocal

behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science*, *15*, 65-

84.

Luís, A. R., Couchinho, M. N., & dos Santos, M. E. (2016). A Quantitative Analysis of Pulsed

Signals Emitted by Wild Bottlenose Dolphins. *PLOS ONE*, *11*(7), e0157781.

Madsen, P. T., & Surlykke, A. (2013). Functional Convergence in Bat and Toothed Whale Biosonars. *Physiology*, *28*(5), 276–283.

Marian, A. (2020). *Long-term Passive Acoustics as a Novel Approach to Assess Spatial and Temporal Patterns of Atlantic Common Bottlenose Dolphins (Tursiops Truncatus) in the May River Estuary, South Carolina* [MSc Thesis].

Marley, S. A., Salgado Kent, C. P., & Erbe, C. (2016). Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging, and environmental variables within a highly urbanised estuary. *Hydrobiologia*, *792*(1), 243–263

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Jarvis, S., Morrissey, R. P., Ciminello, C.-A., & DiMarzio, N. (2010). Spatially explicit capture–recapture methods to estimate minke whale density from data collected at bottom-mounted hydrophones. *Journal of Ornithology*, *152*(S2), 445–455.

McCabe, E. J. B., Gannon, D. P., Barros, N. B., & Wells, R. S. (2010). Prey selection by resident common bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, Florida. *Marine Biology,* 157, 931–942.

Mellinger, D., Stafford, K., Moore, S., Dziak, R., & Matsumoto, H. (2007). An Overview of Fixed Passive Acoustic Observation Methods for Cetaceans. *Oceanography*, *20*(4), 36–45.

Miller, P. J. O., Johnson, M. P., & Tyack, P. L. (2004). Sperm whale behavior indicates the use of echolocation click buzzes ‘creaks’ in prey capture. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *271*(1554), 2239–2247.

Monczak, A, Berry, A., Kehrer, C., & Montie, E. (2017). Long-term acoustic monitoring of fish calling provides baseline estimates of reproductive timelines in the May River estuary, southeastern USA. *Marine Ecology Progress Series*, *581*, 1–19.

Monczak, A, Mueller, C., Miller, M., Ji, Y., Borgianini, S., & Montie, E. (2019). Sound patterns of snapping shrimp, fish, and dolphins in an estuarine soundscape of the southeastern USA. *Marine Ecology Progress Series*, *609*, 49–68.

Monczak, Agnieszka, McKinney, B., Mueller, C., & Montie, E. W. (2020). What’s all that racket! Soundscapes, phenology, and biodiversity in estuaries. *PLOS ONE*, *15*(9), e0236874.

NOAA. (2013). *Charleston harbor becomes 23rd to use NOAA PORTS® data system [RR] | National Oceanic and Atmospheric Administration*. Noaa.Gov. Available online at <https://www.noaa.gov/charleston-sc-harbor-becomes-23rd-use-noaa-ports%C2%AE-data-system>. Accessed 26 October 2020.

Nuuttila, H., Meier, R., Evans, P. G. H., Turner, J. R., Bennell, J. D., & Hiddink, J. G. (2013). Identifying Foraging Behaviour of Wild Bottlenose Dolphins (*Tursiops truncatus*) and Harbour Porpoises (*Phocoena phocoena*) with Static Acoustic Dataloggers. *Aquatic Mammals*, *39*(2), 147–161.

Pate, S. M., & McFee, W. E. (2012). Prey Species of Bottlenose Dolphins (*Tursiops truncatus*) from South Carolina Waters. *Southeastern Naturalist*, *11*(1), 1–22.

Pirotta, E., Laesser, B. E., Hardaker, A., Riddoch, N., Marcoux, M., & Lusseau, D. (2013). Dredging displaces bottlenose dolphins from an urbanised foraging patch. *Marine Pollution Bulletin*, *74*(1), 396–402.

Pirotta, E., Merchant, N. D., Thompson, P. M., Barton, T. R., & Lusseau, D. (2015). Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity. *Biological Conservation*, *181*, 82–89.

Rogers, T. L., Ciaglia, M. B., Klinck, H., & Southwell, C. (2013). Density Can Be Misleading for Low-Density Species: Benefits of Passive Acoustic Monitoring. *PLoS ONE*, *8*(1), e52542.

Roh, H.-S., Sutin, A., & Bunin, B. (2008). Determination of acoustic attenuation in the Hudson River Estuary by means of ship noise observations. *The Journal of the Acoustical Society of America*, *123*(6), EL139–EL143.

SCDNR SEAMAP. (2000). *Results of Trawling Efforts in the Coastal Habitat of the South Atlantic Bight*. Available online at http://www.dnr.sc.gov/marine/mrri/SEAMAP/ SMreports.html. Accessed 8 October 2020.

Simard, P., Wall, C. C., Allen, J. B., Wells, R. S., Gowans, S., & Forys, E. A. (2015). Dolphin Distribution on the West Florida Shelf Using Visual Surveys and Passive Acoustic Monitoring. *Aquatic Mammals*, *41*(2), 167–187.

Simon, M., Nuuttila, H., Reyes-Zamudio, M. M., Ugarte, F., Verfub, U., & Evans, P. G. H. (2010). Passive acoustic monitoring of bottlenose dolphin and harbour porpoise, in Cardigan Bay, Wales, with implications for habitat use and partitioning. *Journal of the Marine Biological Association of the United Kingdom*, *90*(8), 1539–1545.

Smott, S., Monczak, A., Miller, M. E., & Montie, E. W. (2018). Boat noise in an estuarine soundscape – A potential risk on the acoustic communication and reproduction of soniferous fish in the May River, South Carolina. *Marine Pollution Bulletin*, *133*, 246–260.

Speakman, T., Zolman, E., Adams, J., Defran, R. H., Laska, D., Schwacke, L., Craigie, J., & Fair, P. (2006). *Temporal and Spatial Aspects of Bottlenose Dolphin Occurrence in Coastal and Estuarine Waters near Charleston, South Carolina*. NOAA Technical Memorandum NOS NCCOS 37.

‌

Speakman, T. R., Lane, S. M., Schwacke, L. H., Fair, P. A., & Zolman, E. S. (2010). Mark-recapture estimate of seasonal abundance and survivorship for bottlenose dolphins (*Tursiops truncatus*) near Charleston, South Carolina, USA. *Journal of Cetacean Research and Management*, 11, 153–162.

Torres, L. G., McLellan, W. A., Meagher, E., & Pabst, D. A. (2005). Seasonal distribution and

relative abundance of bottlenose dolphins, *Tursiops truncatus*, along the US mid-Atlantic Coast.

*Journal of Cetacean Research and Management*, *7*(2), 153–161.

Toth, J. L., Hohn, A. A., Able, K. W., & Gorgone, A. M. (2010). Patterns of seasonal occurrence, distribution, and site fidelity of coastal bottlenose dolphins (*Tursiops truncatus*) in southern New Jersey, U.S.A. *Marine Mammal Science*, *27*(1), 94–110.

U.S. Army Corps of Engineers. (2015). *Charleston Harbor Post 45 Final Integrated Feasibility Report/Environmental Impact Statement* (pp. 1–386). Available online at <https://www.sac.usace.army.mil/Portals/43/docs/civilworks/post45/finalreport/1_Main%20Report%20and%20EIS.pdf>. Accessed 12 September 2020.

US Census Bureau. (2010). *Census.gov*. Census.Gov. https://www.census.gov/

‌

Waring, G. T., E. Josephson, K. Maze-Foley, P. E. Rosel, editors. (2016). Atlantic and Gulf of Mexico marine mammal stock assessments—2015. *NOAA Tech. Rep. NMFS.*

Weinpress‐Galipeau, M., Baker, H., Wolf, B., Roumillat, B., & Fair, P. A. (2021). An adaptive

bottlenose dolphin foraging tactic, “shipside feeding,” using container ships in an urban estuarine

environment. *Marine Mammal Science*, *37*(3), 1159–1165. https://doi.org/10.1111/mms.12806

Wenner, E. L., Coon III, W. P., Shealy Jr., M. H., & Sandifer, P. A. (1984). Five-year study of seasonal distribution and abundance of fishes and decapod crustaceans in the Cooper River and Charleston Harbor, South Carolina, prior to diversion. *NOAA Technical Report NMFS SSRF-782.*

van Ginkel, C., Becker, D. M., Gowans, S., & Simard, P. (2017). Whistling in a noisy ocean: bottlenose dolphins adjust whistle frequencies in response to real-time ambient noise levels. *Bioacoustics*, *27*(4), 391–405.

Zolman, E. S. (2002). Residence Patterns of Bottlenose Dolphins (Tursiops truncatus) in the Stonot River Estuary, Charleston County, South Carolina, U.S.A. *Marine Mammal Science*, *18*(4), 879–892.

**TABLES AND FIGURES**

**Table 1** Breakdown of generalized linear models (GLMs) used in analyses of each bottlenose dolphin vocalization type relationship with total dolphins sighted.

**Table

Description automatically generated**

*Note.* All models fit with a Gaussian distribution and Log+1 transformation of the response variable.

**Table 2** ANOVA Summary of significance table of the models described ran as multiple linear regressions to obtain theses values due to GLMs fitting Gaussian distribution best.

**Table

Description automatically generated**

*Note.* All models fit with a Gaussian distribution and Log+1 transformation of the response variable.

**Table 3** Further breakdown of model fit and variable significance, models described ran as multiple linear regressions to obtain these values due to GLMs fitting Gaussian distribution best.

**A screenshot of a computer

Description automatically generated with low confidence**

*Note.* All models fit with a Gaussian distribution and Log+1 transformation of the response variable.

**Table 4** Bottlenose dolphin visual detections and sighting abundance spatial trends across all sites surveyed within the Charleston Harbor, SC from Dec 2017 to May 2019.

Table

Description automatically generated

*Note.* Visual detections = the number of sightings/surveys on which dolphins were surveyed for; Total dolphins = total dolphins sighted; Survey effort = total time spent on sightings in minutes across all surveys; Sighting rate = Total number of dolphins sighted divided by survey effort.

**Table 5** Bottlenose dolphin acoustic detections and vocalization abundance spatial trends across all sites surveyed within the Charleston Harbor, SC from Dec 2017 to May 2019.

Table

Description automatically generated

*Note*. Total files = the total number of acoustic files in which vocalizations were detected; % = number of detections divided by the number of files analyzed; Total vocalizations = sum of all vocalizations identified and counted in WAV files for each vocalization type; % = the summed detections of each vocalization type divided by the sum of all vocalization types; Detection rate = Total number of vocalizations detected divided by survey effort.

**Table 6** Bottlenose dolphin visual detections and sighting temporal trends across seasons surveyed within the Charleston Harbor, SC from Dec 2017 to May 2019.

**Table

Description automatically generated**

*Note.* Visual detections = the number of sightings/surveys on which dolphins were surveyed for; Total dolphins = total dolphins sighted; Survey effort = total time spent on sightings in minutes across all surveys; Sighting rate = Total number of dolphins sighted divided by survey effort.

**Table 7** Bottlenose dolphin acoustic detections and vocalization abundance temporal trends across all seasons surveyed within the Charleston Harbor, SC from Dec 2017 to May 2019.

**Table

Description automatically generated**

*Note*. Total files = the total number of acoustic files in which vocalizations were detected; % = number of detections divided by the number of files analyzed; Total vocalizations = sum of all vocalizations identified and counted in WAV files for each vocalization type; % = the summed detections of each vocalization type divided by the sum of all vocalization types; Detection rate = Total number of vocalizations detected divided by survey effort.

**Figure 1** Map of passive acoustic recorder site locations stationed throughout the study area, the Charleston Harbor, SC.

Map

Description automatically generated

Graphical user interface, chart, line chart

Description automatically generated**Figure 2** Partial correlation coefficient model estimates of the relationship between vocalization and dolphin abundance while accounting for spatial, temporal, and biological factors using Dec 2017 to May 2019 time series in Charleston Harbor, SC.

**A picture containing calendar

Description automatically generatedFigure 3** Mean (+–95% Confidence Interval) total dolphins sighted (top) or vocalizations sampled bimonthly across six sites in the Charleston Harbor from Dec 2017 to May 2019.

*Note.* Means with different letters are significantly different (Tukey’s HSD, p < 0.05).

**A picture containing engineering drawing

Description automatically generatedFigure 4** Mean (+–95% Confidence Interval) total dolphins sighted (top) or vocalizations sampled bimonthly across seasons in the Charleston Harbor from Dec 2017 to May 2019.

*Note.* Means with different letters are significantly different (Tukey’s HSD, p < 0.05).

**Figure 5** Mean (+–95% Confidence Interval) total dolphins sighted (top) and total vocalizations (bottom) sampled bimonthly, grouped seasonally across all six sites surveyed in the Charleston Harbor from Dec 2017 to May 2019.

A sheet of music

Description automatically generated with low confidence

**Figure 6** Mean (+–95% Confidence Interval) total dolphins sighted (top) and total echolocation bouts (bottom) sampled bimonthly, grouped seasonally across all six sites surveyed in the Charleston Harbor from Dec 2017 to May 2019.

Diagram

Description automatically generated

**Figure 7** Mean (+–95% Confidence Interval) total dolphins sighted (top) and total burst pulses (bottom) sampled bimonthly, grouped seasonally across all six sites surveyed in the Charleston Harbor from Dec 2017 to May 2019.

Diagram

Description automatically generated

**Figure 8** Mean (+–95% Confidence Interval) total dolphins sighted (top) and total whistles (bottom) sampled bimonthly, grouped seasonally across all six sites surveyed in the Charleston Harbor from Dec 2017 to May 2019.

Diagram

Description automatically generated

**SUPPLEMENTAL TABLES AND FIGURES**

**Table S.1** Generalized linear model results and variable importance determined by likelihood ratio chi-square tests.

**Table

Description automatically generated**

**Figure S.1** Map of passive acoustic recorder site locations stationed throughout the study area, the Charleston Harbor, SC with dolphin sightings (grouped by group size) overlaid spanning Dec 2017 to May 2019.

Map

Description automatically generatedMap

Description automatically generated