



Spatiotemporal trends in bottlenose dolphin foraging behavior and relationship to environmental variables in a highly urbanized estuary

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ABSTRACT: Marine predator foraging influences community structure and ecosystem functions, which are all linked with environmental variables. Determining variables that are associated with foraging can facilitate the identification of important habitats, which is particularly important in heavily urbanized systems. In the New York–New Jersey Harbor Estuary, bottlenose dolphins *Tursiops truncatus* are exposed to various stressors, including vessel activity and forthcoming offshore wind development. Here, we used passive acoustic monitoring to identify foraging conditions for dolphins from April–October of 2018–2020. When foraging, dolphins produce a series of rapid clicks ('foraging buzzes') which can be used as a proxy for foraging activity. We analyzed the relationship between acoustic detections of dolphins and environmental variables using a generalized additive modeling framework. The variables week, sea surface temperature (SST), and chlorophyll *a* (chl *a*) concentration were significantly associated with foraging activity at seasonal timescales. Foraging increased with increasing SST and water levels, with the peak of foraging occurring in autumn. The relationship between chl *a* concentration and foraging was not straightforward and warrants further research. Diel foraging trends varied seasonally and annually. These results suggest that passive acoustic monitoring and environmental variables may be used to investigate marine mammal behavior and assess seasonal foraging habitat for marine predators within dynamic, heterogeneous, and human-dominated environments. Baseline data on dolphin habitat use is vital given the continued expansion of anthropogenic activities and climate-driven shifts in oceanographic conditions that are occurring in this region.

KEY WORDS: *Tursiops truncatus* · Passive acoustic monitoring · Foraging dynamics · Cetacean · Habitat use · Estuarine

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1. INTRODUCTION

The foraging dynamics of apex predators influence the structure of ecological communities and how the ecosystem functions (Franco-Trecu et al. 2017). In turn, the abiotic, biotic, and anthropogenic components of the ecosystem influence how it is used by

predators (Hastie et al. 2004, Cubero-Pardo 2007, Methion & López 2019). In marine environments, the distribution of apex predators has been linked with both dynamic and static characteristics of habitats (Hastie et al. 2004), including sea surface temperature (SST; Becker et al. 2010), bathymetry (Forney et al. 2012, Thorne et al. 2017), and productive up-

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wellings (Doniol-Valcroze et al. 2007). Estuaries, which experience a range of environmental variability, can provide important habitat for apex predators due to their high productivity (Moreno & Matthews 2018). Tidal fluxes in estuaries mix fresh and sea water and carry nutrients, which support fish abundance (Pirani et al. 2018). However, prey distribution in estuaries is often patchy (Seymour et al. 2009). Prey availability is therefore assumed to be an important factor of habitat preference, as the movements of predators likely mirror the behavior of prey species (Boyd et al. 2015).

Environmental variables are commonly used as a proxy for understanding prey distribution in marine environments, as distribution data are not readily available due to sampling challenges (Torres et al. 2008, Becker et al. 2010, Forney et al. 2012, Nurdin et al. 2013, Thorne et al. 2017, Pérez-Jorge et al. 2020). Predators may also use environmental features related to prey presence as cues while searching for prey (Vaughn-Hirshorn 2019). For example, Blainville's beaked whales *Mesoplodon denirostris* appear to preferentially forage in areas with steep topography where they can feed on a mixture of meso- and benthopelagic prey, sometimes during a single dive (Arranz et al. 2011). Moreover, by using environmental variables that are associated with prey presence, it is possible to accurately assess dynamic changes in the environment that affect spatial and temporal variations in foraging behavior of marine predators, as opposed to designating foraging habitat as a static feature within a dynamic and heterogeneous environment (Torres et al. 2008, Miller & Baltz 2009). These assessments can then be used to inform conservation and management efforts, which is particularly relevant in the context of climate change and the expansion of anthropogenic activities (Torres et al. 2008, Moreno & Matthews 2018).

Bottlenose dolphins *Tursiops truncatus* are globally distributed from tropical to temperate latitudes (Wells et al. 2019) and are among the most well-studied mammalian predators found in estuaries (Moreno & Matthews 2018). Due to their high productivity, estuaries may encompass important foraging habitat for bottlenose dolphins (Moreno & Matthews 2018). However, these dolphins spend most of their time underwater, making it difficult to visually assess their foraging activity (Vaughn-Hirshorn 2019). This may be further compounded by the challenges of surveying within urbanized estuaries. As an alternative, foraging behavior of bottlenose dolphins can be estimated by measuring rates of known foraging-related vocalizations (Pirodda et al. 2015). Bottlenose dolphins

echolocate by producing clicks as they navigate and forage, and different rates of click repetition can be used to differentiate between the various uses of echolocation (Pirodda et al. 2015, Marian et al. 2021). When foraging, there is a decrease in inter-click intervals (ICIs; the time between clicks) as dolphins approach their prey item, creating a vocalization referred to as a 'foraging buzz' (Pirodda et al. 2015, Cascão et al. 2020, Fandel et al. 2020, Marian et al. 2021). These foraging buzzes can be used as a proxy for foraging activity (Miller et al. 2004, Madsen et al. 2005, Pirodda et al. 2015) and aid in identifying foraging activity. This is particularly useful in turbid waters where visibility is limited and dolphins are expected to rely more heavily on acoustic sensing (Wells 2019). Henceforth, when we refer to foraging activity, we are describing foraging buzz ICI detections. In other locations, this method has provided critical knowledge of where and when marine mammals are foraging (Pirodda et al. 2014, Simonis et al. 2017, Fandel et al. 2020). By linking acoustic indicators of dolphin foraging with environmental variables, it is possible to investigate fine-scale spatial and temporal patterns in foraging activity in relation to natural variations within the environment without the limitations imposed by visual observation-based methods (Fandel et al. 2020, Marian et al. 2021).

The New York–New Jersey Harbor Estuary (hereafter NY–NJ Harbor Estuary) is a heavily urbanized estuary (Pirani et al. 2018) that is used seasonally by bottlenose dolphins (Hayes et al. 2021). The estuary supports the largest and most densely populated city in the USA, providing a public resource to more than 14 million people (Pirani et al. 2018). Bottlenose dolphins that migrate seasonally to the NY–NJ Harbor Estuary belong to the Western North Atlantic Northern Migratory Coastal stock (Hayes et al. 2021). Though bottlenose dolphins are considered a species of Least Concern by the IUCN (Wells et al. 2019) and are not listed as threatened or endangered by the US Endangered Species Act, this stock is considered a strategic stock due to its designation as depleted under the US Marine Mammal Protect Act (Hayes et al. 2021). Currently, it is thought that dolphins belonging to this stock occupy coastal habitat from Assateague (Virginia) to Long Island (New York) during warm-water months and migrate south to North Carolina during cold-water months, where they overlap spatially and temporally with other stocks (Whitt et al. 2015, Hayes et al. 2021). Along their range, this stock occupies habitat adjacent to highly urbanized and industrialized areas, but the

potential anthropogenic impacts on these dolphins are not well understood (Hayes et al. 2021).

The migration of these dolphins to the northernmost part of their range is thought to be largely driven by prey availability and/or water temperature gradients (Toth et al. 2011). As the Northwest Atlantic experiences increasing water temperatures due to climate change (Kleisner et al. 2017), there may be related shifts in bottlenose dolphin distribution and migration patterns (Stinnette et al. 2018). Coincidentally, bottlenose dolphins have recently been observed more frequently and for longer periods in the NY–NJ Harbor Estuary and surrounding waters (Stinnette et al. 2018). This may be influenced by climate-related changes (Kleisner et al. 2017), efforts to restore habitat quality (Pirani et al. 2018, Taillie et al. 2020), and/or a recovery of Atlantic menhaden *Brevoortia tyrannus* stocks, an important prey item of marine mammals in the mid-Atlantic (Lucca & Warren 2018, Stinnette et al. 2018). While bottlenose dolphin presence may be increasing in these waters, very little is known about how this stock uses the habitat within and around the NY–NJ Harbor Estuary (Stinnette et al. 2018).

The lack of baseline scientific data on bottlenose dolphin habitat use in the waters of New York and New Jersey is concerning in light of current and forthcoming anthropogenic disturbances and climate-driven changes in the coastal waters of the Northwest Atlantic. For instance, these waters are used by multiple maritime industries, including shipping, fishing, tourism, and upcoming developments in offshore wind energy (BOEM 2020), all of which have potential impacts on marine mammals in this area (e.g. Brown et al. 2019, King et al. 2021, Stepanuk et al. 2021, Smith et al. 2022). It is therefore imperative to better understand bottlenose dolphin habitat use and migratory patterns as well as what environmental factors may be driving the observed patterns.

The objectives of our study were to address these knowledge gaps by (1) investigating spatiotemporal trends in foraging activity in and around the NY–NJ Harbor Estuary and (2) evaluating the relationships between environmental variables and foraging activity at both seasonal and diel scales. We conducted passive acoustic monitoring and collated environmental variables that have been previously linked to foraging behavior in other locations, including chlorophyll *a* (chl *a*) concentration (Scott et al. 2010), SST (Methion & López 2019), lunar phase (Simonis et al. 2017), bathymetry (Hastie et al. 2004, Bailey & Thompson 2010), distance to shore (Moreno & Mat-

thews 2018), water level (Gregory & Rowden 2001), and temporal variables, including hour of day and time of year (Methion & López 2019, Cascão et al. 2020). We hypothesized that foraging activity would be similarly related to these environmental variables in the NY–NJ Harbor Estuary (Table S1 in the Supplement at www.int-res.com/articles/suppl/m690p219_supp.pdf). Evaluating spatiotemporal trends in dolphin foraging and determining associations between environmental conditions and foraging activity provides critical information for identifying and predicting ecologically important areas and times (Torres et al. 2008). This information is particularly important in areas where bottlenose dolphin habitat use and anthropogenic activity heavily overlap (Torres et al. 2008, Methion & López 2019), such as the NY–NJ Harbor Estuary.

2. MATERIALS AND METHODS

2.1. Study area

This study took place in and around the NY–NJ Harbor Estuary, which extends from Sandy Hook, NJ, to Far Rockaway, NY (Fig. 1; Boicourt et al. 2016). Passive acoustic archival recorders were strategically deployed at 6 study sites (NJ1–NJ2, NY1–NY4) in and around the NY–NJ Harbor Estuary (Fig. 1). The estuary can be divided into the Upper and Lower Bays; 4 sites (NJ1, NJ2, NY1, and NY3) were located in the Lower Bay, NY2 was located in the Upper Bay, and NY4 was located outside of the estuary near a man-made reef (Rockaway Reef) where there have been numerous bottlenose dolphin sightings (Fig. 1; Wildlife Conservation Society unpubl. data). Across these study sites, there are variations in depth (7–12 m), slope (0.044–1.57°), and distance to shore (0.124–4.47 km). The NY–NJ Harbor Estuary experiences seasonal fluctuations in SST (Balcom et al. 2008) and spatiotemporal variations in chl *a* concentration (Taillie et al. 2020). The study area has gradations in water quality that mirror oceanic flushing patterns caused by tidal action (Taillie et al. 2020). Water quality is highest near the mouth of the estuary (NJ2 and NY3) and degrades with increasing distance to the estuary mouth (NJ1 and NY2; Taillie et al. 2020). This area also encompasses the Port of New York–New Jersey, which is the third-largest port operation in the USA (Pirani et al. 2018). Vessel traffic varies spatially and temporally across the study area, and all sites except NY4 were in areas with high vessel traffic (Fig. 1).

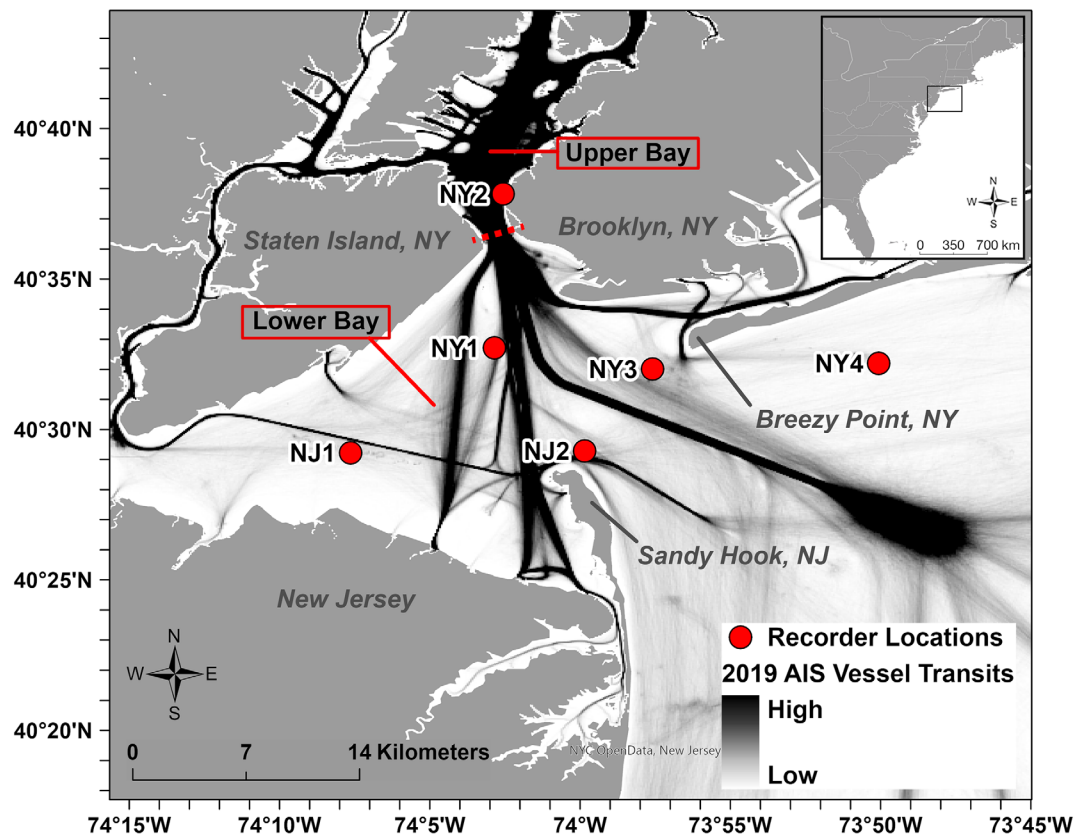


Fig. 1. New York–New Jersey Harbor Estuary and surrounding waters. Red circles: the 6 study sites (NJ1, NJ2, NY1, NY2, NY3 and NY4); grayscale gradient: 2019 vessel density (darker colors indicate areas with increased overlap in vessel transits based on automatic identification system [AIS] tracks); red dashed line: Verazzano Bridge, which connects Brooklyn, NY, to Staten Island, NY, and separates the Upper and Lower Bay

2.2. Acoustic data collection

Archival passive acoustic monitoring devices (Ocean Instruments SoundTrap ST300 HF) were repeatedly deployed at the 6 study sites, with a total of 6 recorder deployments spanning from October 2018 to October 2020 (Table 1). Recorders were deployed at NJ1 for deployments 1–5 (Table 1). At NJ2, NY1, and NY3, recorders were deployed for all 6 deployments, and recorders were deployed at NY2 and NY4 for deployments 3–5 (Table 1). In 2020, extended gaps in data were due to the delayed recovery and deployment of units because of the COVID-19 global pandemic, which required extra logistical constraints and safety measures. Recorders were moored in the water column ~1.5 m above the seafloor. To enhance battery life and data storage capacity, the units recorded at a duty cycle of 20 min every 60 min and at a sampling rate of 96 kHz, allowing for monitoring across a 48 kHz frequency bandwidth. Due to some equipment failure during deployments, not all units recorded for the

entire duration of the deployment (Table 1). Additionally, we restricted the analysis to data collected from 1 April to 31 October, as this timeframe captures the months when dolphins are known to be in the area, including the peak in abundance (Whitt et al. 2015), but excludes months when other odontocete species may be using the NY–NJ Harbor Estuary (Whitt et al. 2015, M. L. Rekdahl unpubl. data). The second deployment occurred outside of this timeframe and was therefore entirely excluded from the analysis.

2.3. Acoustic data processing

To distinguish bottlenose dolphin clicks from noise and other odontocete species, a custom click detector was developed in the PAMGuard Click Detector module (v.2.01.03; Gillespie et al. 2008) following methods outlined in Pirotta et al. (2015). Clicks were classified as being produced by a bottlenose dolphin if the click length was between 0–0.2 ms, the

Table 1. Days used in this study of bottlenose dolphins from each recorder and each deployment that included data collection between 1 April and 31 October

Location	Deployment	Start date	End date	No. of days included
NJ1	1	5 October 2018	31 October 2018	27
	3	1 April 2019	17 July 2019	109
	4	26 July 2019	14 October 2019	81
	5	26 October 2019 ^a	3 May 2020 ^a	39
NJ2	1	5 October 2018	31 October 2018	27
	3	18 April 2019	14 May 2019	27
	4	26 July 2019	15 October 2019	82
	5	25 October 2019 ^a	16 April 2020 ^a	23
	6	1 July 2020	7 August 2020	38
NY1	1	5 October 2018	31 October 2018	27
	3	5 April 2019	17 July 2019	105
	4	26 July 2019	15 October 2019	82
	5	25 October 2019	31 October 2019	7
	6	1 July 2020	6 October 2020	98
NY2	3	5 April 2019	17 July 2019	105
	4	26 July 2019	15 October 2019	82
	5	25 October 2019	31 October 2019	7
NY3	1	5 October 2018	31 October 2018	27
	3	18 April 2019	17 July 2019	91
	4	26 July 2019	14 October 2019	81
	5	25 October 2019 ^a	21 April 2020 ^a	28
	6	1 July 2020	6 October 2020	98
NY4	3	5 April 2019	17 July 2019	105
	4	26 July 2019	15 October 2019	82
	5	26 October 2019	31 October 2019	6

^aDates from these deployments that were outside of 1 April and 31 October were excluded

energy in the test frequency band 15–48 kHz was 18 dB louder than the energy in the control frequency band 0–5 kHz, the mean frequency for the search and integration range 0–48 kHz was between 10–48 kHz, and there were 0–10 zero crossings (Pirota et al. 2015). Due to the size of the data set and the labor-intensive process of validating the accuracy of the click detector, the acoustic data were subsampled to every 4th hour of every 4th day. From that subset, a random 5% of files were manually reviewed aurally and in Raven (Hann window, fast Fourier transform (FFT): 1024, 50% overlap, 0–48 kHz). Because the recorders were on a duty cycle of 20 min per 60 min, each 20 min audio file was representative of 1 h of the day. The analysis with the finest temporal resolution was conducted at the file level (i.e. hourly); thus, the percent agreement between the detector and manual review was calculated at this temporal resolution. We compared how many times the output of the manual review and automated detector matched with regard to whether or

not a file contained dolphin clicks. We found 80% agreement when comparing the automated detector and manual review outputs.

2.4. Environmental data

Environmental covariates were determined for each location and deployment. We calculated distance to shore (km), slope (°), and depth (m) in ArcGIS Pro v.10.7.1 (ESRI) using the bathymetry map from the ESRI Living Atlas database (www.esri.com; Table S1). We used the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) data set from the UK Met Office to determine SST (°C; Table S1). We determined surface chl *a* concentration (mg m⁻³) using NOAA's Visible Infrared Imaging Radiometer Suite (VIIRS) sensor (Table S1). Weekly lunar phase values (% illumination) were derived from the Moon Phase and Libration data sets from NASA's Scientific Visualization Studio (Table S1). The mean weekly value for surface chl *a* concentration and SST was determined using a 1 km radius around each recorder for each deployment. Due to the skew of the mean weekly surface

chl *a* concentration, the values were log-transformed. Hourly water level information was collected from NOAA's Tides and Currents data set (Table S1).

2.5. Statistical analyses

2.5.1. Mean foraging buzz threshold

Once dolphin clicks were detected and classified by the automated detector in PAMGuard, the binary files with detected clicks were imported into R v.3.4.3 (R Core Team 2020). Given the presumed noisy environment of the NY–NJ Harbor Estuary and the sensitivity of the SoundTrap recorders (Sarnocinska et al. 2016), we conservatively classified dolphin-positive hours (DPHs) as those with at least 50 detected dolphin clicks to reduce the likelihood of including false positives in the analyses. From these DPHs, we calculated ICIs across all recorders and deployments and examined the fre-

quency distribution (Fig. S1). Bottlenose dolphins produce echolocation clicks during multiple behaviors (Herzing 1996), but here our primary interest was to identify clicks produced during foraging buzzes using ICIs (Pirodda et al. 2014, 2015, Fandel et al. 2020). Based on methods outlined by Pirodda et al. (2014), ICIs were clustered into 3 groups: regular ICIs (for clicks produced for navigation and searching for prey), buzz ICIs (for clicks in foraging buzzes produced during attempted prey captures), and inter-train ICIs (for time between click trains). A Gaussian mixture model was fitted to the log-transformed distribution of ICIs in order to group different echolocating processes and determine the mean foraging buzz ICI (Reynolds 2009, Pirodda et al. 2014; Fig. S2). Following the methods used in Pirodda et al. (2014), the Gaussian mixture model indicated a mean foraging buzz threshold of 3 ms, and we used this threshold in our analysis when determining the presence of foraging buzz ICIs in the data. Using the mean buzz ICI as a threshold for determining the occurrence of foraging buzzes may have resulted in the exclusion of some foraging buzz ICIs that fall between the mean and maximum of the buzz ICI distribution, but we decided to use this metric as it is more conservative and would reduce the potential for including regular ICIs in the analysis.

2.5.2. Spatiotemporal variation in dolphin presence and foraging activity

DPHs were classified as those containing at least 50 dolphin clicks with ICIs of any duration, including buzz ICIs, regular ICIs, and inter-train ICIs. As a subset of DPHs, hours containing at least one foraging buzz ICI (ICI \leq 3 ms) were considered foraging-positive hours (FPHs). Dolphin-positive days (DPDs) were classified as days with at least one DPH but no FPHs (i.e. dolphins were present but not foraging), and days containing at least one FPH were classified as foraging-positive days (FPDs; i.e. dolphins were both present and foraging). To examine overall spatial trends in dolphin presence and foraging activity, we calculated the proportion of DPDs and FPDs relative to the total number of recording days per location, respectively. To investigate overall temporal variations in foraging activity, we calculated the proportion of FPDs relative to the total recording days per month at each location. Peaks in foraging activity at each location were defined as months that had a proportion of FPDs \geq 0.70.

2.5.3. Environmental influences on foraging activity

A generalized additive modeling approach was used to investigate foraging activity at both seasonal and diel scales. For the seasonal model, foraging activity was investigated on a weekly basis due to the resolution of the environmental data. Every week was matched with a season (spring, summer, and autumn; defined below) as well as the mean weekly chl *a* concentration, SST, and lunar phase value. Seasonal trends were investigated from 1 April to 31 October using the calendar dates of the equinox and solstice for 2018–2020, resulting in the following seasonal divisions: spring (1 April–21 June 2019; 1 April–20 June 2020), summer (22 June–23 September 2019; 21 June–22 September 2020), and autumn (23 September–31 October 2018 and 2020; 24 September–31 October 2019). Weeks split between seasons were assigned to the season that had the highest proportion of days represented. For the diel model, we determined the presence or absence of foraging buzz detections in DPHs.

For both the seasonal and diel data sets, covariance between continuous independent variables was assessed by constructing a Pearson correlation matrix in R. If environmental covariates had a correlation coefficient with an absolute value greater than 0.5, we selected the more biologically relevant covariate to use in the model (Thorne et al. 2012). For the seasonal analysis, covariates included location, week number (1–52), depth (m), slope ($^{\circ}$), season, distance to shore (km), weekly mean lunar phase (% illumination), weekly mean SST ($^{\circ}$ C), and the log-transformed weekly mean surface chl *a* concentration (mg m^{-3}). Diel covariates included location, water level (ft), year (2018–2020), month (April–October), and hour of the day (0–23). None of the correlation coefficients of the covariates exceeded 0.5 for the seasonal or diel data sets; thus, all covariates were retained in both models (Tables S2 & S3).

When investigating overall spatiotemporal trends in foraging activity, FPDs were calculated from the total days recorded (see Section 2.5.2). We then built upon these findings by examining the relationship between environmental variables and foraging activity only during weeks with dolphins present to avoid confounding presence and foraging. We investigated seasonal dynamics in foraging activity with binomial generalized additive mixed models (GAMMs) using the 'gamm' function in the 'mgcv' package (v.1.8.38; Wood 2011, 2021), as this method can account for temporal autocorrelation in time series measurements (Simonis et al. 2017). GAMMs were conducted using

a binomial distribution with a logit link function. Weeks without at least one DPD were excluded from the analysis, and the weekly proportions of FPDs were calculated from the remaining weeks, ranging between 0 (no days with foraging buzz detections) and 1 (foraging buzz detections during every day of that week). We addressed the temporal autocorrelation in the seasonal data by including an autoregressive model of order one (AR-1) correlation structure with residuals nested by week for computational efficiency. Weeks were weighted by the number of full recording days that had dolphins present (between 1 and 7), and the week covariate used a cyclic cubic regression spline. Chl *a* concentration and SST were grouped by season to examine potential seasonal variation in their relationships to foraging activity.

For the diel analysis, hourly presence of foraging buzz detection was investigated using binomial generalized additive models (GAMs) using the ‘gam’ function in the ‘mgcv’ package due to the poor performance of GAMMs when analyzing binary data (Wood 2021). In the diel GAMs, the positive detection of at least one foraging buzz and no detection of a foraging buzz within an hour was scored as 1 and 0, respectively (Pirodda et al. 2014). Similarly to the seasonal analysis, GAMs were conducted using a binomial distribution with a logit link function, and hours without dolphins present were excluded from the diel analysis to avoid confounding dolphin presence with foraging activity. The hour of the day covariate used a cyclic cubic regression spline and was grouped by season to examine potential seasonal variability. Hour of the day was also included as a random effect.

We ran the full model containing all covariates for both the seasonal and diel analyses. We conducted a backward stepwise removal of all variables that had a *p*-value > 0.5 based on the output of the full models and ranked the model iterations by Akaike’s information criterion (AIC; Wagenmakers & Farrell 2004). The model with the lowest AIC was considered the most parsimonious model and was used in the final analysis (Bursac et al. 2008; Tables S4 & S5).

3. RESULTS

3.1. Spatiotemporal variation in dolphin presence and foraging activity

Bottlenose dolphins were frequently detected in the NY–NJ Harbor Estuary, with dolphins present during more than half of the recorded days (0.51–0.71); similar levels of foraging activity were detected

(0.41–0.62) at all locations except NY2, where dolphin detections were rare (Fig. 2). Dolphin presence and foraging activity (DPDs and FPDs, respectively) were highest at NY3 compared to the other recording sites (Fig. 2). NY1 had the second highest proportion of DPDs (0.62) but the third highest proportion of FPDs (0.53; Fig. 2), as NJ2 had the second highest proportion of FPDs relative to total days recording (0.55; Fig. 2). Dolphins foraged in the majority of days during which dolphin presence was detected; the proportion of FPDs relative to DPDs was greater than 0.75 at all locations except NY2, where dolphin foraging was detected in 2 out of the 3 days that dolphin presence was detected. There was some spatial variability in foraging trends across months and years, although there was a general peak in foraging activity across most sites from late summer to autumn (July–October). NY3 had a high level of foraging activity from July–September 2019, which then shifted to August–October in 2020, although there was still a relatively high level of foraging in July 2020 (0.61; Table 2). At NJ1 and NY1, foraging activity peaked in August and September 2019 and August–October 2020 at NY1 (Table 2). In 2019, NY4 had more foraging activity in the spring relative to the other sites and peaked in September (Table 2). Foraging activity at NJ2 peaked later in the season in 2019, during September and October (Table 2). In 2020, foraging activity decreased from July to August at NJ2, while the opposite trend was observed at NY1 and NY3 (Table 2). Interestingly, the peaks in foraging activity were not necessarily consistent

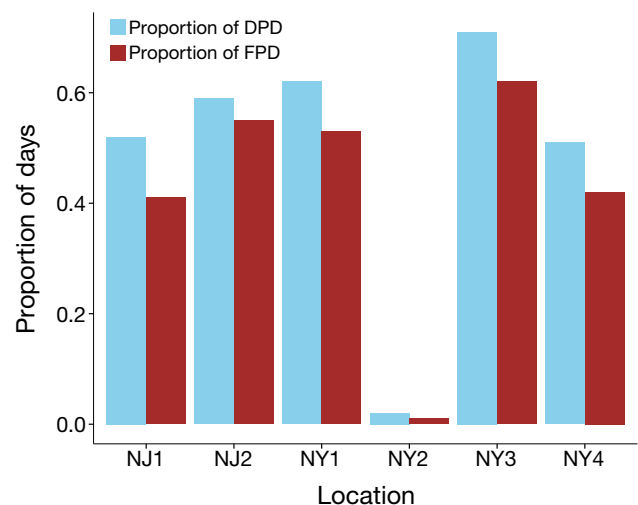


Fig. 2. Proportion of dolphin-positive days (DPDs) and foraging-positive days (FPDs) relative to the total number of recording days during the months of April–October at each location (See Fig. 1)

Table 2. Proportion of bottlenose dolphin foraging-positive days (FPD) relative to the total number of recording days for each month at each location. Peaks in foraging activity (≥ 0.70) are highlighted in **bold**; (–) no data

Location	2018	2019				2020									
	Oct	Apr	May	Jun	Jul	Aug	Sep	Oct	Apr	May	Jun	Jul	Aug	Sep	Oct
NJ1	0.63	0.07	0.19	0.46	0.26	0.84	0.77	0.05	0.03	0	–	–	–	–	–
NJ2	0.70	0.08	0.21	–	0.33	0.48	0.93	0.81	0.31	–	–	0.52	0.14	–	–
NY1	0.33	0.04	0.06	0.17	0.35	0.90	0.77	0.29	–	–	–	0.65	0.97	0.97	1.0
NY2	–	0	0	0	0	0	0.07	0	–	–	–	–	–	–	–
NY3	0.59	0.15	0.06	0.23	0.74	0.84	0.87	0.67	0.62	–	–	0.61	0.97	0.80	1.0
NY4	–	0.23	0.23	0.43	0.48	0.45	0.70	0.43	–	–	–	–	–	–	–

across years, and foraging activity at NY1 and NY3 was generally higher in 2020 than in 2019 (Table 2). NY2 had only 2 FPDs throughout the entire study period, both in September 2019 (Table 2).

3.2. Environmental influences on foraging activity

3.2.1. Seasonal trends

The most parsimonious seasonal model included chl *a* concentration, SST, slope, and week as significant covariates for foraging activity (Table 3). Chl *a* concentration only had a significant correlation with foraging in the spring ($F = 3.62$, $p < 0.05$; Table 3). In spring, the probability of detecting foraging activity was highest (0.89) at low chl *a* concentrations (4 mg m^{-3}) and decreased as chl *a* concentrations increased until an inflection point was reached at 19 mg m^{-3} , after which foraging activity gradually increased with increasing chl *a* concentrations (Fig. 3A). SST had a significant positive correlation with foraging during autumn ($F =$

11.74 , $p < 0.001$) but not spring or summer (Table 3). Dolphins were first detected in April, when SST was as low as 6°C , and they continued to be detected through the last day of our study period (31 October), when the SST was approximately 14°C . Throughout their seasonal presence, dolphins experienced SSTs ranging from 6 – 26°C . Though SST was not a significant variable in the spring ($p = 0.46$), the probability of detecting foraging activity in spring surpassed 0.5 when SST was 14°C and the peak probability reached 0.61 when SST increased to 20°C (Fig. 3B). In summer ($p = 0.39$), the probability of detecting foraging activity gradually increased during the summer from 0.69 at 20°C until the peak probability of 0.78 at 26°C (Fig. 3D). The rate of foraging activity steadily decreased between 22 and 14°C in autumn, with the probability of detecting foraging activity dropping below 0.5 at approximately 18°C (Fig. 3F). Foraging decreased with increasing slope ($F = 20.72$, $p < 0.001$; Fig. 3G). Lastly, week was significantly correlated with foraging activity ($F = 3.95$, $p < 0.001$; Fig. 3H). This model had an R^2 value of 0.47.

Table 3. Most parsimonious generalized additive mixed model (GAMM) used to explore variation in the foraging buzz production of bottlenose dolphins in the New York–New Jersey Harbor Estuary over seasonal scales. DAY: mean weekly proportion of foraging-positive days during weeks with at least one dolphin-positive day; chl-*a*: log-transformed weekly mean chl *a* concentration (mg m^{-3}); SST: weekly mean sea surface temperature; week: week number (1–52); significant p -values ($p < 0.05$) are in **bold**

Terms included	Significance of parametric coefficients				Significance of smooth terms					Model fit	
	Intercept	SE	<i>t</i>	<i>p</i>	Term	EDF	df	<i>F</i>	<i>p</i>	R^2	AIC
DAY ~ s(chl- <i>a</i> , by season) + s(SST, by season) + s(slope) + s(week)	0.67	0.26	2.53	0.01	Chl- <i>a</i> : spring	2.18	2.18	3.62	0.02	0.47	651.1
					Chl- <i>a</i> : summer	1	1	0.26	0.61		
					Chl- <i>a</i> : autumn	1	1	0.51	0.48		
					SST: spring	1	1	0.56	0.46		
					SST: summer	1	1	0.75	0.39		
					SST: autumn	1	1	11.74	<0.001		
					Slope	1	1	20.72	<0.001		
					Week	2.05	8	3.95	<0.001		

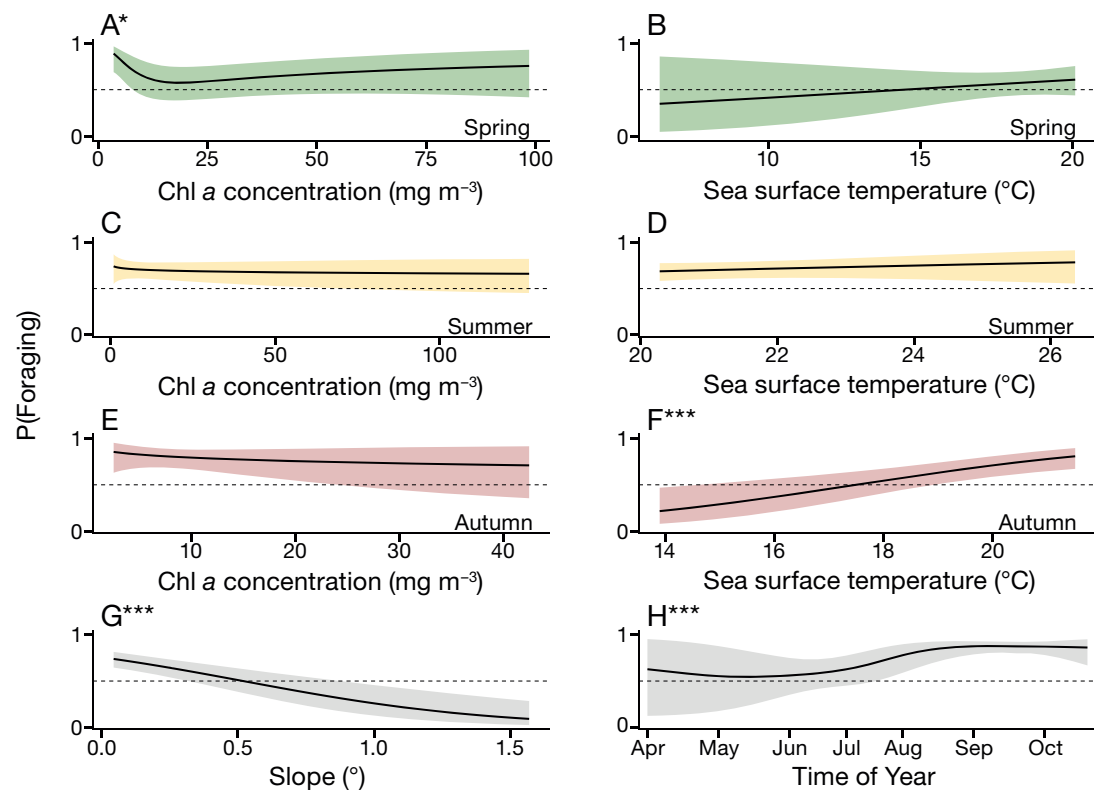


Fig. 3. Most parsimonious seasonal model showing the estimated relationship between the probability of detecting bottlenose dolphin foraging activity and environmental covariates, including chl a concentration in (A) spring (C) summer, and (E) autumn, sea surface temperature in (B) spring, (D) summer, and (F) autumn, (G) slope, and (H) week (time of year). While week number was used in the analysis, month is shown on the x-axis in (H) for ease of interpretation. Dashed lines: 50 % probability that dolphins are foraging when they are present; shaded regions: 95 % confidence intervals. The significance of the plotted relationship is denoted by asterisks, and the number of asterisks indicates the level of significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

3.2.2. Diel trends

The most parsimonious diel model included all covariates, and all variables but year were significant (Table 4). Hour of the day had a significant effect on foraging activity in summer ($\chi^2 = 7.90$, $p < 0.01$), where dolphin foraging activity was lowest around 10:00 h and increased to a slight peak at 23:00 h (Fig. 4B). In spring, diel trends in foraging activity were more variable, with peaks in foraging at 02:00 and 13:00 h, and reduced foraging around 08:00 and 19:00 h ($\chi^2 = 6.94$, $p = 0.10$; Fig. 4A). Hourly foraging trends were similar but less pronounced in the autumn, with peaks at 03:00 and 15:00 h, and reduced foraging activity at 08:00 and 21:00 h ($\chi^2 = 2.36$, $p = 0.55$; Fig. 4C). By month, foraging was detected significantly more often in September (coefficient = 0.65, $p < 0.001$) and October (coefficient = 0.68, $p < 0.01$) relative to April (Table 4) and, though not significant, foraging was higher in 2020 relative to 2018 (coefficient = 0.34, $p = 0.10$; Table 4). Water level was also significantly re-

lated to foraging activity ($\chi^2 = 18.05$, $p < 0.01$; Table 4). Foraging was reduced at the minimum water levels, moderate at intermediate water levels, and increased at maximum water levels (Fig. 4D). Foraging activity was significantly higher at NJ2 (coefficient = 0.98, $p < 0.001$) and NY4 (coefficient = 0.94, $p < 0.001$) relative to NJ1. Altogether, this model had an R^2 value of 0.05.

4. DISCUSSION

Our results provide substantial new ecological knowledge about bottlenose dolphin habitat use in and around the NY–NJ Harbor Estuary, including spatiotemporal trends in foraging and the relationships between environmental variables and acoustic presence. Bottlenose dolphins are seasonally present in the waters of New York and New Jersey from April–October (Whitt et al. 2015, Hayes et al. 2021), and here we documented foraging activity during

Table 4. Most parsimonious generalized additive model (GAM) used to explore variation in the foraging buzz production of bottlenose dolphins in the New York–New Jersey Harbor Estuary over diel scales. BUZZ: presence/absence of foraging buzzes in each dolphin-positive hour; loc: location (NJ1, NJ2, NY1, NY2, NY3, and NY4); hour: hour of the day (0–23); water: water level (ft); significant p-values ($p < 0.05$) are in **bold**

Terms included	Significance of parametric coefficients					Significance of smooth terms					Model fit	
	Term	Estimate	SE	z	p	Term	EDF	df	χ^2	p	R ²	AIC
BUZZ ~ loc + year + month + s (hour, by season) + s (water)	Intercept	-0.19	0.26	-0.71	0.47	Water	5.26	6.41	18.05	<0.01	0.05	4535.6
	Loc: NJ2	0.98	0.15	6.46	<0.001	Hour: spring	3.88	18	6.94	0.10		
	Loc: NY1	0.16	0.13	1.29	0.20	Hour: summer	1.99	18	7.90	<0.01		
	Loc: NY2	-0.14	1.23	-0.11	0.91	Hour: autumn	3.07	18	2.36	0.55		
	Loc: NY3	0.09	0.12	0.73	0.46							
	Loc: NY4	0.94	0.18	5.23	<0.001							
	Year: 2019	0.03	0.19	0.17	0.87							
	Year: 2020	0.34	0.20	1.66	0.10							
	Month: May	-0.42	0.33	-1.25	0.21							
	Month: June	-0.09	0.27	-0.35	0.73							
	Month: July	-0.04	0.20	-0.21	0.84							
	Month: August	0.31	0.19	1.65	0.10							
	Month: September	0.65	0.19	3.51	<0.001							
	Month: October	0.68	0.22	3.11	<0.01							

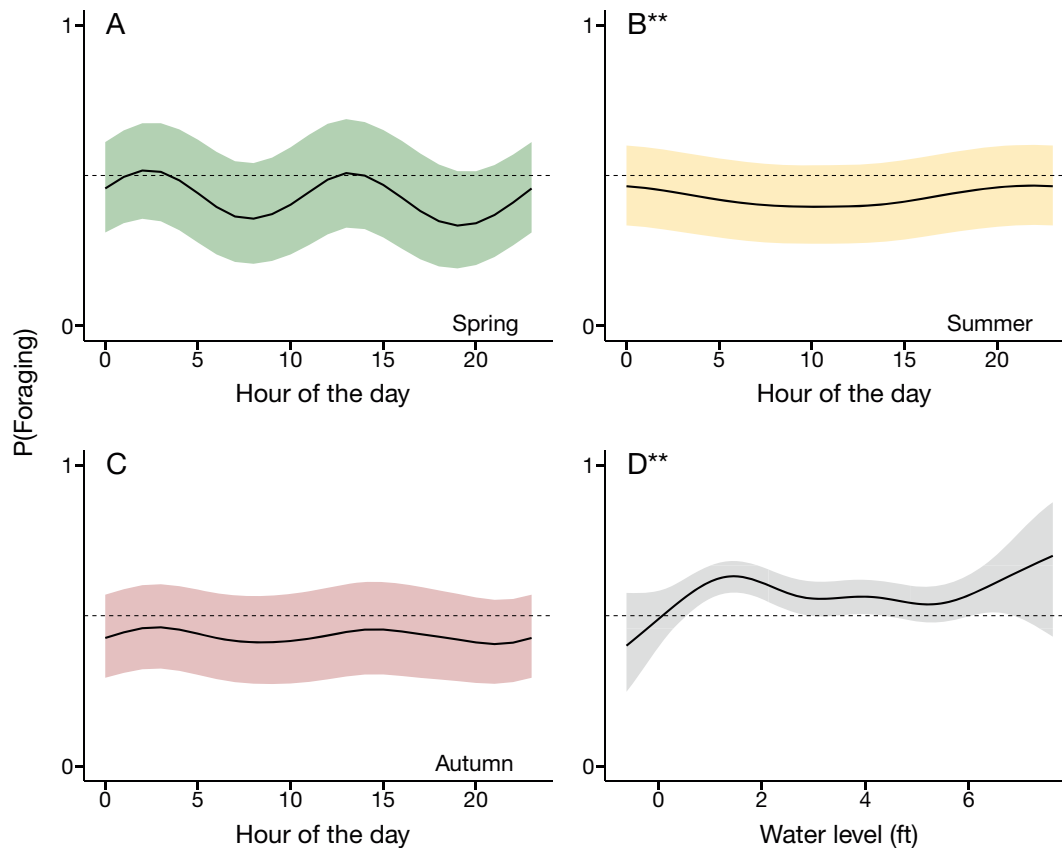


Fig. 4. Most parsimonious diel model showing the estimated relationship between the probability of detecting bottlenose dolphin foraging activity and environmental covariates, including hour of the day in (A) spring, (B) summer, and (C) autumn, and (D) water level (1 ft = approximately 0.3 m). Dashed lines: 50% probability that dolphins are foraging when they are present; shaded regions: 95% confidence intervals. The significance of the plotted relationship is denoted by asterisks, and the number of asterisks indicates the level of significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

the majority of days with dolphin presence. These results suggest that the NY–NJ Harbor Estuary may serve as a foraging ground for this migratory population. This is congruent with the notion that seasonal migrations of Atlantic bottlenose dolphin populations are driven, at least partially, by prey availability (Whitt et al. 2015, Taylor et al. 2016). In our study, a general peak in dolphin foraging activity was found in late summer to autumn (July–October), suggesting that this period may encompass the most favorable conditions for dolphin foraging in the NY–NJ Harbor Estuary area.

While the NY–NJ Harbor Estuary may generally serve as a foraging ground, there were some spatiotemporal variations in foraging activity throughout the study area. Although foraging activity was generally highest during late summer and autumn, there were some minor variations; foraging activity at times peaked during different months at different sites, and seasonal peaks at the same site were not necessarily consistent across years. These fine-scale variations in foraging activity may reflect patchy spatiotemporal distributions of prey across the NY–NJ Harbor Estuary, with dolphins shifting their foraging effort accordingly. We found that overall, dolphins appeared to heavily use the Lower Bay, particularly near the mouth of the estuary (NJ2 and NY3) to forage. Estuary mouths have been previously identified as hotspots for bottlenose dolphin presence and foraging activity, including in South Carolina (Marian et al. 2021), Texas (Moreno 2005), Florida (Simard et al. 2015), Mexico (Ballance 1992), and Scotland (Pirotta et al. 2014), which may reflect favorable conditions in these areas for preferred prey species (Taylor et al. 2016, McBride-Kebert et al. 2019) or may be a consequence of the topography, such as a bottleneck effect for fish migrating through the area (Hastie et al. 2004, Bailey & Thompson 2010).

Topography and hydrography can influence prey distribution and interact to aggregate prey in certain areas, and these areas may be used more heavily by bottlenose dolphins to optimize foraging effort (Bailey & Thompson 2010). In the UK, for example, bottlenose dolphins prefer to forage in areas with steep seabed gradients, potentially because steep slopes can be used to herd prey (Bailey & Thompson 2010). In contrast, we found foraging activity decreased with increasing slope, although this may be due to our small sample size for slope, as there was only one value for slope for each location and deployment and recorders were deployed in the same location repeatedly. The NY–NJ Harbor Estuary generally does not have large variability in seabed gradients, although

the shipping channels within the harbor are dredged, which may create artificially steep slopes that allow denser prey patches to form and attract foraging cetaceans (e.g. Smith et al. 2022). However, we were unable to deploy recorders in these channels, so the relationship between steeper slopes and dolphin foraging activity is unclear in this area and warrants further investigation.

It does appear that landscape features at the mouth of the estuary may constrict water flow, yielding higher vorticity and stronger currents that potentially increase prey encounter rates and foraging success (Bailey & Thompson 2010). Out of the 6 study sites, NJ2, NY2, and NY3 were located in high current areas relative to the other sites. In comparison with NJ2 and NY3, which had the highest prevalence of foraging activity and were located near the estuary mouth, NY2 rarely had days with acoustic detections of dolphin presence, and foraging activity was even more rarely detected. While NY2 experiences strong currents that could increase prey concentration, the benefits may be outweighed by the potential costs of foraging in an area with high levels of anthropogenic activity. Shipping traffic in this area may lead to area avoidance by bottlenose dolphins or the underwater noise produced by ships may acoustically mask dolphin vocalizations (Erbe et al. 2019). If acoustic masking is occurring, it could prohibit detection if clicks are being produced, or dolphins may cease vocalizing. Alternatively, because water quality degrades with distance to the mouth of the estuary (Taillie et al. 2020), dolphins and/or their preferred prey may be avoiding NY2 due to the lower quality of the water in the Upper Bay. Beyond observing a general preference for foraging in high current areas, we found that foraging activity increased during intermediate and maximum water levels, perhaps reflecting a preference for the directionality of water currents while foraging (Bailey & Thompson 2010).

In addition to topographical and hydrological features that potentially aggregate prey, the spatiotemporal variability in foraging activity may also reflect favorable environmental conditions for prey species (Taylor et al. 2016, McBride-Kebert et al. 2019). Environmental conditions that have been correlated with prey presence, including surface chl *a* concentration and SST (Nurdin et al. 2013), were found to be significant factors influencing dolphin foraging in this study. Interestingly, chl *a* concentration was only significantly related to foraging activity in the spring, which may be due to seasonal migration into the study area while searching for prey. Our finding that foraging activity was highest when chl *a* concentra-

tion was low (4 mg m^{-3}) is consistent with a previous study in Florida, where dolphin presence peaked at approximately 3 mg m^{-3} (Torres et al. 2008). This may indicate that lower concentrations of chl *a* were more suitable for prey species, or that there were temporal lags between changes in chl *a* concentration and prey species aggregating (Grémillet et al. 2008). Furthermore, high chl *a* concentrations may lead to eutrophication, resulting in prey area avoidance or prey mortality (Karim et al. 2003). In this study, however, foraging activity also increased when chl *a* concentrations were very high (exceeding 19 mg m^{-3}). The underlying mechanisms influencing this relationship are unclear, especially considering that chl *a* concentrations greater than 20 mg m^{-3} are considered very unhealthy in the NY–NJ Harbor Estuary (Taillie et al. 2020). The correlations between dolphin foraging activity, prey presence, and chl *a* concentrations are therefore not straightforward and warrant further study in the dynamic NY–NJ Harbor Estuary environment.

Dolphin foraging activity was also strongly influenced by SST in the NY–NJ Harbor Estuary. In the Western North Atlantic Northern Migratory Coastal stock, SST is not considered a direct influence on the seasonal movement to the northernmost part of their range, as dolphins are able to tolerate cooler water temperatures than those associated with migration in this stock (Toth et al. 2011). For instance, the range of SSTs provided for bottlenose dolphins that inhabit coastal waters of North America is about $10\text{--}32^\circ\text{C}$ (Wells et al. 2019), but in the coastal waters of New Jersey and Virginia, migration appears to be triggered by SSTs of $\sim 14\text{--}16^\circ\text{C}$ (Barco et al. 1999, Toth et al. 2011). In the NY–NJ Harbor Estuary, the lowest SST associated with acoustic detections of bottlenose dolphin presence was 6°C , which is $8\text{--}10^\circ\text{C}$ cooler than the SSTs associated with the first and last visual sightings of bottlenose dolphins in the waters of coastal New Jersey (Toth et al. 2011). This difference may reflect the limitations of visual observation methods (including a potential sampling bias towards warmer weather), variations in prey availability in the coastal and estuarine systems studied (Toth et al. 2011), or differences in the distributions of preferred prey species (Taylor et al. 2016) and potential predators, which are also likely influenced by environmental variables (Yeates & Houser 2008). However, similar to other studies on migratory coastal Atlantic populations, bottlenose dolphin presence in this study was most commonly detected when SST was above 14°C , during the summer ($20\text{--}26^\circ\text{C}$) and autumn ($14\text{--}22^\circ\text{C}$) months (Barco et al. 1999,

Toth et al. 2011, Taylor et al. 2016, McBride-Kebert et al. 2019).

Given that the probability of detecting foraging activity was generally greater than 50% when SST was above 18°C , the temperature range most conducive to dolphin foraging in the NY–NJ Harbor Estuary may be between 18 and 26°C during the seasons where dolphins are more abundant. This range is similar to the SST range associated with bottlenose dolphin foraging activity in the Gulf of Mexico ($20\text{--}24^\circ\text{C}$; Miller & Baltz 2009). Variation in SST ranges associated with dolphin foraging may reflect preferences for prey species that have different thermal tolerances; thus, understanding spatiotemporal differences in water temperature preferences, particularly as it relates to foraging, may contribute to a better understanding about which prey species dolphins are targeting in the study area.

In the NY–NJ Harbor Estuary, dolphin foraging activity increased throughout the summer and into the autumn, with a slight decrease towards the end of October as the southward migration began. Week was likely a significant factor in foraging activity, as it reflected the migration of dolphins into and out of the NY–NJ Harbor Estuary. Therefore, week could potentially be used as a determinant of dolphin foraging activity, particularly when considered alongside environmental variables such as SST. Interestingly, in the NY–NJ Harbor Estuary and surrounding waters, bottlenose dolphin foraging activity mirrored the peak in abundance and biomass of Atlantic menhaden found by Lucca & Warren (2019). Furthermore, juvenile Atlantic menhaden are typically observed in low-salinity areas, such as near the mouths of estuaries (Taylor et al. 2016), which is where we found the highest prevalence of foraging activity. This spatiotemporal match suggests that Atlantic menhaden may serve as important prey for this population of bottlenose dolphins as they do for other marine mammal species in the area (Stinnette et al. 2018, King et al. 2021). The co-occurrence of bottlenose dolphins and Atlantic menhaden in the NY–NJ Harbor Estuary was also found using environmental DNA (eDNA; Alter et al. 2022). In fact, when analyzing fish sequences, Atlantic menhaden were found in 100% of the analyzed samples, contributing the highest percentage of fish DNA (mean: 94%, range: 5–99%; Alter et al. 2022). While Atlantic menhaden were not as common as Sciaenidae prey species in the diet composition of stranded dolphins in North Carolina, they were found in the stomachs of 19% of the 180 dolphins analyzed (Gannon & Waples 2004), suggesting that they may be a prey species of interest for

bottlenose dolphins in the Mid-Atlantic, and in the NY–NJ Harbor Estuary in particular.

Overall, seasonal patterns in foraging activity were well-explained by the variables included in this study; thus, using these environmental variables as a proxy for prey availability at broad temporal scales may contribute to assessments of foraging habitat, though more work is needed to understand the underlying ecological processes driving these relationships. Furthermore, knowing the ranges of environmental conditions that are conducive to foraging activity will allow for some degree of predictive capacity when assessing potential foraging habitat for bottlenose dolphins in the waters of New York and New Jersey. Coupling favorable foraging conditions (including the range of SSTs associated with foraging, defined in this study as 18–26°C) with seasonal peaks in dolphin foraging activity (July–October) and spatial preferences for dolphin foraging (near the mouth of the estuary) provides important baseline information about seasonal habitat use in the NY–NJ Harbor Estuary, which can then be used to inform mitigation measures and conservation efforts that operate on seasonal timescales.

Diel trends in foraging activity were found to demonstrate annual and seasonal variability, which may reflect changes in prey distribution and behavior (Marian et al. 2021) and potentially differences in anthropogenic disturbance. For example, the worldwide reduction in marine traffic during the COVID-19 pandemic (March et al. 2021), which had an associated reduction in underwater noise in other large North American ports (Thomson & Barclay 2020), may have contributed to differences in diel foraging trends observed in 2020. There may have been an increase in the detection range of dolphin vocalizations if ambient underwater noise levels were reduced and/or there was an increase in foraging activity in response to the presumed vessel traffic reduction, which may explain why more foraging activity was detected in 2020 relative to 2018 and 2019.

The R^2 value of the most parsimonious diel model was very low, and therefore it is likely that other factors, such as vessel activity, are influencing the observed variation in foraging activity throughout the day. Hourly patterns in foraging activity may be influenced by vessel presence and/or vessel noise (Pirodda et al. 2015), especially in areas where there is both high food availability and high levels of anthropogenic pressure (Methion & López 2019), such as the NY–NJ Harbor Estuary. In highly urbanized systems where dolphins are more likely to interact with

vessels, foraging activity may be disrupted by vessel presence (Pirodda et al. 2015), and repeated disruptions of foraging activity can lead to reduced energy intake, with potential consequences for survival and fitness (New et al. 2013). Vessel noise can also mask bottlenose dolphin vocalizations used for communication and prey detection, reducing foraging opportunities (Jensen et al. 2009). In the Moray Firth, where bottlenose dolphins regularly forage and vessel traffic is high, the probability of detecting a bottlenose dolphin foraging buzz was reduced by almost half when vessels were passing (Pirodda et al. 2015). Given the similar conditions of the NY–NJ Harbor Estuary and the limited explanatory power of the variables selected here, more focused research on the impacts of anthropogenic activity on diel trends in dolphin foraging activity is needed.

While passive acoustic monitoring allows for data collection during times and over timescales that would not be possible with visual observation (Fandel et al. 2020), this method has limitations. Firstly, click detection is dependent on dolphins vocalizing, and their acoustic behavior can be affected by many factors, including anthropogenic activity and prey behavior (Marian et al. 2021). When dolphin clicks are being produced, click detection by the recorders may be influenced by conditions in the environment, such as sediment type, which influence sound propagation through water (Pirodda et al. 2014, Marian et al. 2021), acoustic masking by natural influences, such as storms (Fandel et al. 2020) or snapping shrimp (Simard et al. 2015), and/or behavioral state (Herzing 1996). For example, bottlenose dolphins can produce buzzes during social interactions as well as during prey capture events, though social buzzes are more likely to be missed by the recorders due to their higher directionality (Pirodda et al. 2014) and are therefore unlikely to significantly impact our results (Herzing 1996). Because echolocation clicks are highly directional, they could be missed by the archival passive acoustic recorders if they were not received at the correct angle (Pirodda et al. 2014) or may be missed or misclassified by the automated click detector module during post-processing. This could lead to an underestimation of foraging activity, especially on fine temporal scales, which may partially explain why diel models had a worse performance compared to the seasonal models (Pirodda et al. 2014). Given the high directionality of echolocation clicks and the noisy environment of the NY–NJ Harbor Estuary, it was not possible to explore metrics that quantify the intensity of foraging activity (e.g. buzz duration or number of buzzes). Instead, we

chose to use a simpler but more reliable metric (detection of at least one buzz ICI in an hour or day). However, this method may underestimate dolphin foraging activity, as we excluded files containing less than 50 detected dolphin clicks. There were also gaps in our data collection due to equipment failure and logistical constraints associated with the COVID-19 global pandemic which should be taken into consideration when interpreting results. For instance, our data set had some spatial and temporal biases, as more data was collected from the New York sites, during the summer season, and during 2019.

Overall, the methods used in this study yielded important information about dolphin foraging activity in the NY–NJ Harbor Estuary, and future studies can build upon these findings. Future studies would benefit from incorporating acoustic data with visual observations of bottlenose dolphin behavior in the NY–NJ Harbor Estuary and investigating a wider repertoire of behaviors. To understand whether the environmental conditions conducive to dolphin foraging activity are stable across space, future research should explore the relationships between foraging buzz detection and environmental variables at broader spatial scales (i.e. across the entire migratory range of the Western North Atlantic Northern Migratory Coastal stock). In the highly urbanized NY–NJ Harbor Estuary, it is vital that future work investigates the potential impacts of anthropogenic disturbances (such as vessel noise and vessel presence) on foraging activity, particularly at fine temporal scales (i.e. hourly or daily). While data on the potential impacts of offshore wind development on bottlenose dolphins are sparse, various impacts on harbor porpoise *Phocoena phocoena* have been documented in Europe (e.g. Brandt et al. 2011, 2018, Nabe-Nielsen et al. 2018, Benhemma-LeGall et al. 2021), and these 2 species have demonstrated similar sensitivities to frequencies associated with pile-driving (Thomsen et al. 2006). In the Moray Firth, during periods of piling activity coastal bottlenose dolphins spent less time in areas exposed to piling noise (Graham et al. 2017). Thus, there is a time-sensitive need to conduct more focused studies on bottlenose dolphins in areas where there are anticipated overlaps between bottlenose dolphins and offshore wind energy development and anthropogenic activities that support development, such as port expansion, cabling energy to shore, and increased vessel traffic. Additionally, investigating bottlenose dolphin diet composition in the NY–NJ Harbor Estuary and surrounding waters would be invaluable for understanding trophic dynamics by

providing more information relating to the interactions between primary production, prey aggregations, and dolphin foraging, in addition to providing insight on how bottlenose dolphins may be influencing community structure within this urbanized ecosystem. Overall, considering the warming SSTs and the expansion of offshore wind development in the waters of New York and New Jersey, more focused research is needed on this understudied population of bottlenose dolphins in order to better manage potential human–wildlife conflict.

5. CONCLUSIONS

Passive acoustic monitoring proved effective for monitoring spatiotemporal variations in habitat use of bottlenose dolphins in the NY–NJ Harbor Estuary, and the results of this study provide valuable baseline data for further research and monitoring efforts, including investigating potential impacts from anthropogenic disturbances in this region. The use of environmental variables to estimate when and where dolphins may forage can contribute to the development of mitigation measures, such as implementation of noise reduction approaches and other recommended best practices during important times for these marine predators. As the Northwest Atlantic experiences climate-driven shifts in oceanographic conditions and prey fields shift in response, the use of dynamic environmental variables, such as SST, may become increasingly important for assessing potential seasonal foraging habitat for bottlenose dolphins in this region, as their migration patterns and distributions may change. Climate-driven range shifts in these top marine predators may influence biodiversity and trophic dynamics (Fandel et al. 2020), such that baseline knowledge on occurrence and foraging behavior may be used to understand broader impacts on the ecosystems they inhabit. More broadly, these findings contribute to the growing body of research on how passive acoustic monitoring and environmental data may be used to investigate the behavioral ecology of marine predators, particularly in the challenging environments of urbanized estuaries. Understanding how marine predators, such as bottlenose dolphins, are interacting with features of the habitat in these heavily urbanized ecosystems can provide insight into ecosystem functioning and trophic dynamics and guide conservation efforts to mitigate potential human–wildlife conflict.

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