Marine Mammal Science

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Baleen Whale Occurrence in the Waters Off Virginia and North Carolina, U.S.A. From 2001 to 2019

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ABSTRACT

Eighteen years of visual survey and strandings data were used to describe baleen whale occurrence along the continental shelf of Virginia and North Carolina, U.S.A. This region experiences heavy anthropogenic use, which poses risks for mortality and injury to baleen whales. Between 2001 and 2019, six species of baleen whales were recorded, and whales occurred year-round. The total number of (on- and off-effort) sightings and strandings amounted to 838 whales, including humpback (*Megaptera novaeangliae*, $n = 503$), fin (*Balaenoptera physalus*, $n = 197$), North Atlantic right (*Eubalaena glacialis*, NARW, $n = 76$), common minke (*B. acutorostrata*, $n = 51$), sei (*B. borealis*, $n = 10$), and blue (*B. musculus*, $n = 1$) whales. Spatial modeling and abundance estimates indicated whale density and distribution changed seasonally. The highest densities of all whales combined occurred in winter and spring. Across seasons, average densities were highest in the northern portion of the study area. Ninety percent of NARW sightings were outside the designated Seasonal Management Areas in place for their protection. The stranding record offered a complementary view of species richness and seasonality. This study provides a baseline of baleen whale occurrence in an area experiencing increasing anthropogenic pressures (e.g., ship traffic and offshore wind-energy development).

1 | Introduction

Survey and stranding data collected over an 18-year period were used to investigate the distribution and abundance of multiple species of baleen whales along the coasts of Virginia and North Carolina, U.S.A. (see Figure 1 for study area). The coastal and offshore waters of these mid-Atlantic states are heavily utilized by the shipping (U.S. Department of Commerce 2018) and commercial fishing industries, and increasingly, the energy sector (e.g., wind energy and seismic geophysical exploration; BOEM 2022). Norfolk, Virginia, in the southern Chesapeake Bay hosts the world's largest U.S.

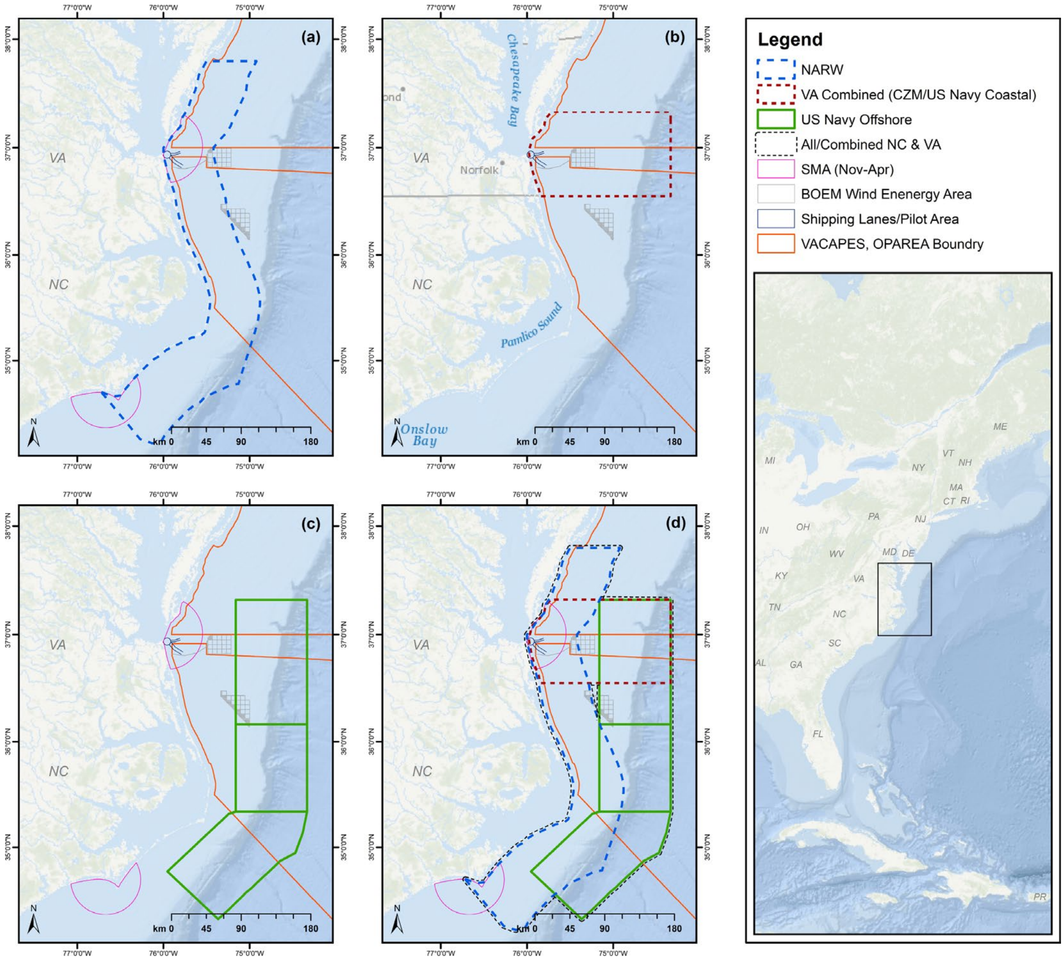

FIGURE 1 | Boundaries for aerial survey projects synthesized in this manuscript, including (a) North Atlantic right whale (NARW) surveys (dashed blue), (b) Virginia (VA) Combined Coastal surveys, that is, surveys funded by VA Coastal Zone Management (CZM) and the U.S. Navy (dashed red), (c) US Navy Offshore surveys (solid green), and (d) Study Area Boundary including all survey sites off the coasts of North Carolina (NC) and VA (black dashed perimeter demarcates the complete Study Area) the Spatial modeling utilized data aerial surveys displayed in (b, c), while the remaining analyses include sightings documented within the combined NC and VA survey perimeter (d). Legend acronym definitions: Seasonal Management Area (SMA); Bureau of Ocean and Energy Management (BOEM); U.S. Navy Virginia Capes Operating Area (VACAPES OPAREA). See Appendix S1.

Naval Military Installation and the third largest shipping port along the U.S. Atlantic coast. Frequent military training and testing operations occur in coastal and offshore waters (U.S. Department of the Navy 2022) and another major port, the Port of Baltimore (Maryland) requires ships to funnel vessel traffic through shipping lanes into the Chesapeake Bay. Cumulatively these activities result in intense vessel traffic through the mouth of the Chesapeake Bay. Two active wind energy leases also fall within the study area: the Coastal Virginia Offshore Wind project (CVOW), located off the mouth of the Chesapeake Bay; (BOEM 2024) and Kitty Hawk Wind (offshore of northern North Carolina; Figure 1; BOEM 2022). In May 2024, installation began on 176 wind turbines in the CVOW lease area off the coast of Virginia, which is currently the largest single wind development site for one company in the U.S. These diverse anthropogenic activities pose potential risks to baleen whales that visit these waters (e.g., RWSC (Regional Wildlife Science Collaborative for Offshore Wind) 2024; BOEM 2023; Jensen et al. 2003; Laist et al. 2001; Sharp et al. 2019; van der Hoop et al. 2012; van der Hoop et al. 2015). There is, thus, a need to understand the seasonal occurrence and distribution of baleen whales in this heavily utilized ocean area.

Baleen whales have been documented along the U.S. east coast through visual observation (e.g., Brown et al. 2018; Engelhaupt et al. 2020; King et al. 2021; Palka et al. 2017; Roberts et al. 2016; Swingle et al. 1993; Zoidis et al. 2021), photo-identification (photo-ID; e.g., Barco et al. 2002; Katona and Whitehead 1981; Kraus et al. 1986), satellite telemetry (e.g., Aschettino et al. 2020), stranding records (e.g., Wiley et al. 1995; Sharp et al. 2019), and passive acoustic monitoring efforts (PAM; e.g., Salisbury et al. 2016; Zeh et al. 2020).

Additional studies have demonstrated that the endangered blue (*Balaenoptera musculus*), fin (*B. physalus*), and sei (*B. borealis*) whales tend to be distributed in deep ocean waters throughout the U.S. Atlantic Exclusive Economic Zone (e.g., Clark and Gagnon 2002; Edwards et al. 2015; Roberts et al. 2016), while the critically endangered North Atlantic right whale (*Eubalaena glacialis*, abbreviated hereafter as NARW) appears to be distributed primarily within continental shelf waters (e.g., Gowan and Ortega-Ortiz 2014; Hayes et al. 2021; Roberts et al. 2024). Humpback (*Megaptera novaeangliae*) and minke (*B. acutorostrata*) whales exhibit seasonal differences in their use of shelf and slope habitats (Clark and Clapham 2004; Clark and Gagnon 2002; Hayes et al. 2021; Risch et al. 2013, 2014).

Broad-scale systematic surveys have been conducted along the east coast of the U.S. (e.g., CETAP 1982; Atlantic Marine Assessment Program for Protected Species [AMAPPs]: Palka et al. 2017) to contribute to regional cetacean abundance estimates, habitat modeling, and ocean planning efforts (e.g., Palka et al. 2017; Roberts et al. 2016; MARCO, n.d.: https://portal.midatlanticocean.org/about-us). Data from these broad-scale surveys and the regional distance sampling surveys reported in this study, have also been used to develop cetacean density models for the U.S. east coast, providing a large-scale view of seasonal density and movement of large whales along the Atlantic seaboard (Roberts et al. 2016).

Mid-Atlantic waters off the coasts of Virginia and North Carolina have been primarily recognized as a migratory corridor for multiple species of baleen whales (e.g., LaBrecque et al. 2015), although there is evidence of seasonal foraging by humpback whales off Virginia suggesting that this region serves as a supplemental feeding ground (Aschettino et al. 2020; Barco et al. 2002; Swingle et al. 1993). More recently, increased use of, and shifts in, traditional distributions into mid-Atlantic (New York to North Carolina) waters of species such as humpback whales (Aschettino et al. 2020; Barco et al. 2002; King et al. 2021; Wiley et al. 1995; Zeh et al. 2020), NARW (Davis et al. 2017), and sei whales (Davis et al. 2020; Zoidis et al. 2021) have been documented.

Baleen whales are vulnerable to threats such as vessel strikes and entanglement in fishing gear. These sources of injury and mortality are of particular concern for NARW given their current critically endangered conservation status (e.g., Corkeron et al. 2018; Pace et al. 2017; Reed et al. 2024; Kraus 1990; 2005; 2016). Whale mortality and injury resulting from vessel and/or fisheries interactions have been frequently documented off the mid-Atlantic, including off the Virginia and North Carolina coasts (e.g., Aschettino et al. 2020; Cassoff et al. 2011; Hayes et al. 2021; Knowlton and Kraus 2001; Hamilton et al. 2012; Moore et al. 2013; NOAA 2026a, 2026b, 2026c; Sharp et al. 2019; van der Hoop et al. 2012; Wiley et al. 1995). Recent elevated whale mortalities, including those due to human activities, have resulted in the declaration of three, concurrent Unusual Mortality Events (UME) for humpback whales, NARW, and minke whales in the western North Atlantic (NOAA 2024a; 2024b, 2024c).

To reduce the likelihood of vessel collisions with NARW, Seasonal Management Areas [SMAs; U.S. Federal Register, 73, 60173–60191; NMFS 2008; 78 *Federal Register* (*Fed. Reg.*) 73,726; NMFS 2013] were established by NOAA, requiring large vessels (≥ 65 ft) to reduce speed (≤ 10 knts) when NARWs are seasonally thought to be present in these areas. Within the study area, two SMAs exist, one located off the Chesapeake Bay in Virginia and another off Morehead City, North Carolina at the southern end of the study area. These SMAs are geographically positioned within a 20 nmi (37 km) radius of major ports and are seasonally active between 1 November and 31 April, when NARWs are thought to migrate between feeding grounds in high latitudes in the northeast and calving grounds in southeastern U.S. Atlantic waters (Kenney et al. 1995; Nichols et al. 2008; Winn et al. 1986; NOAA 1994).

Previous studies only used standardized data collection, very specific to the survey conducted. The present study uses a combination of visual survey and stranding datasets collected along the coasts of Virginia and North Carolina between February 2001 and March 2019 (Figure 1) to provide insights into the presence of baleen whales within the study area. Although existing survey efforts and large-scale spatial density models (Roberts et al. 2016) have provided important information, there is value in analyzing finer scale, region-specific survey data and integrating additional sources of available data, such as stranding records reported here which were not incorporated into these previous studies. Together, these data offer a more comprehensive view of and greater resolution to baleen whale occurrence within the mid-Atlantic region.

Spatial density models, based upon data collected during two aerial survey projects (2011–2019), are used to describe whale seasonal density, abundance, and distribution. Data collected from other aerial (2001–2008) and vessel (2007–2017) surveys, and from strandings over the 18-year study period, are used to further characterize the occurrence of baleen whales in the area. The results of these analyses provide an almost two-decade-long integrative baseline of baleen whale occurrence in an area with expanding anthropogenic impacts.

2 | Methods

2.1 | Data Collection

This study synthesized data from three aerial survey projects off the coasts of Virginia and North Carolina between January 2001 and March 2019, one opportunistic nearshore vessel dataset and all records of stranded baleen whales in Virginia and North Carolina (Table S1; see study area in Figure 1). The aerial survey data sets were collected by the University of North Carolina Wilmington (UNCW), the Virginia Aquarium Foundation (VAQF), and HDR Inc., and documented the occurrence of marine mammals, sea turtles, and opportunistically, other sightings such as sharks, rays, and vessels. See Table S2 for yearly summary of all on- and off-effort aerial survey sightings of baleen whales in the study period and study area.

Aerial surveys followed methods for data collection and species identification as described by Read et al. (2014) and McLellan et al. (2018), with systematic effort (Figure S1) along designated transect lines. Surveys were flown in a Cessna 337 Skymaster (fixed-wing aircraft) at a speed of 185 km/h and at an altitude of 305 m. HDR Inc. recorded data digitally on an Apple iPad using *COMPASS* (see Richlen et al. 2019), whereas all other surveys recorded data on paper datasheets, which were later digitized.

The NARW (see Table S1) surveys conducted between 2001 and 2008 did not systematically follow distance sampling protocols, therefore this data set was omitted from spatial density modeling but was used for qualitative assessments of whale occurrence within the study area. The Virginia combined surveys and the U.S. Navy offshore surveys (conducted by VAQF, UNCW and HDR Inc.) spanned the coasts and offshore waters of Virginia and North Carolina and used distance sampling methodology (Buckland et al. 2001), therefore only these two data sets (2011–2019) were used to generate spatial density models (see Table S1). Briefly, the designated transect lines were flown while two independent observers positioned on each side of the plane, equipped with GPS units, scanned for sighting cues. Once a cetacean sighting cue occurred, the position of the plane and the vertical sighting angle were recorded, and the plane broke track to circle the animal(s). When the plane was directly over the animal(s), the position of the plane was recorded, and images were collected to verify species identification, estimate group size, and opportunistically document observations such as behavior (e.g., feeding and defecating) and group associations (e.g., multiple species and mother-calf pairs). Along transect lines each observer used distance sampling protocols and recorded precise time and geographic position of marine mammal sightings and documented any changes in environmental conditions (i.e., visibility, Beaufort Sea State, cloud cover, and glare). Sightings recorded while actively searching on transect lines are identified as "on-effort" while those recorded while transiting to or from the study area or between transect lines, were identified as "off-effort" sightings. Distinguishing between on- and off-effort sightings allows for different types of analyses to be conducted (i.e., on-effort sitings are used for effort-based abundance estimates whereas both on- and off-effort sightings are used in qualitative assessments of species occurrence).

To better understand the presence of humpback whales in the region, VAQF conducted directed vessel cruises along southern Virginia and at the entrance to the Chesapeake Bay during cooler-water months (December through March) providing more intense coverage of nearshore waters (< 25 km from the coast) as compared to aerial surveys. Vessel cruises were conducted on a 23-ft Parker and a 45-ft Doucette research vessel. Geo-referenced positions of whale sightings and species identification were recorded. Effort data were not consistently collected across years; thus, use of the vessel data was limited to comparison of total numbers of whales by platform and qualitative assessment of species occurrence.

Stranding records (documented between 2001 and 2019) provided an additional layer of information on baleen whales in the study area; these data were also used in the qualitative assessments of occurrence. These data include the date and stranding location (i.e., the geo-referenced location where the stranded whale was first reported, not necessarily indicative of the location of death), as well as biological data, such as sex and total body length (TL, measured by skeletal length in centimeters from tip of rostrum to fluke notch). TL was used to estimate the life history class of individuals. Only stranding records classified as Smithsonian Institution (SI) code "fresh" to "moderate" state of decomposition (Geraci and Lounsbury 1993) were used when reporting TL to provide for greater accuracy in TL estimates. Direct examination of the genital region allowed determination of sex for a majority of dead whales.

2.2 | Photo-Identification of NARWs

Photographic images collected during aerial surveys, vessel cruises, and stranding events offered the opportunity to identify individual NARWs. All images were submitted to the North Atlantic Right Whale Catalog (curated by New England Aquarium) for individual identification. Information available on the life-history class and sex for known individual NARWs is summarized in Table S3 to provide insight into the demographics of whales utilizing the study area.

2.3 | Environmental Covariates

Environmental covariates were acquired for geo-referenced baleen whale sightings and effort segments. Bathymetric (*depth*) data in meters were collected from NOAA National Geophysical Data Center using the ETOPO1, 1 Arc-Minute Global Relief Model (ETOP01 2009). A factor (*shelf*), based on *depth*, describing whether the segment was on/off the continental shelf was created with two levels: "on" (i.e., depth < 100 m) or "off" slope (≥ 100 m). NOAA daily Optimum Interpolation Sea Surface Temperatures (*SST*; °C) were obtained at a resolution of 0.25°C (https://coastwatch.pfeg.noaa.gov/errdap/; Figure S2).

2.3.1 | Density and Abundance Estimates

Spatial density modeling and abundance estimation utilized on-effort sighting data from the two aerial survey projects conducted between 2011 and 2019 (see Figure 1b,c; Table S1). The count method of Hedley and Buckland (2004) was implemented to describe the trend in spatial density for baleen whale species recorded in the study area (fin, humpback, minke, NARW, and sei whales grouped together). The blue whale sighting was excluded given there was only a single sighting of this species. The number of individuals in a small area, or segment, along the transect line, adjusted for detection probability, formed the response and was modeled as a function of location and environmental variables. There were too few aerial sightings of most species to build separate models, so estimates using conventional distance sampling methods (Buckland et al. 2001) were calculated for all baleen whale species combined (as above), for endangered whales (fin, NARW, and sei whales), and separately for fin whales.

2.3.1.1 | Probability of Detection. A critical assumption of distance sampling methods is that all groups on the transect (i.e., at zero perpendicular distance) are detected with certainty (Buckland et al. 2001; this is often denoted $g(0) = 1$). If this is not a valid assumption, the overall probability of detection will be overestimated and estimated numbers in segments will be underestimated (Laake et al. 1997; Marsh and Sinclair 1989; Burt et al. 2014).

There is a wide range of $g(0)$ values for baleen whales in the literature, which are likely dependent upon behavioral state (e.g., migrating vs. feeding) and region-specific factors (e.g., turbidity and depth; Forney et al. 1995; Palka 2005). Given the range of published $g(0)$ values and lack of regional and species-specific dive times that would permit calculation of $g(0)$ values, we reported relative seasonal abundances as this study did not account for availability or perception bias (i.e., no $g(0)$ correction was used).

To increase sample size, the perpendicular distances for baleen whale groups were combined and the distribution of distances was used to model how the probability of detection decreased with increasing distance from the transect (Buckland et al. 2001). This assumed that these species had similar detection probability. Perpendicular distances were truncated to avoid a long tail in the detection function. Two forms of the detection function were considered (without adjustment terms): a hazard rate and a half normal, and the form with the lowest Akaike Information Criterion (AIC) value was selected. The models were fitted in R (R Core Team 2024) using the Distance package (Miller et al. 2019).

2.3.1.2 | Modeling Whale Density. The number of individual whales in segment *i* along the transect (with known area) was enumerated and adjusted for detection probability. This formed the response variable in a statistical model to estimate baleen whale density and abundance within the study area. This approach, as opposed to assuming a constant density, models trends in spatial distribution and allows it to vary throughout the region of interest. Counts are often modeled using a Poisson distribution; however, these data were likely to be overdispersed (because, for example, many segments would contain no or very few animals, and a few segments may contain a large, estimated number during periods of migration), so an overdispersed Poisson distribution was used. The mean of the distribution (μ_i) was modeled with location, habitat, and temporal variables as candidate explanatory variables represented as follows:

$$\mu_i = \exp\left(log(a_i) + \beta_0 + \sum_{j}^{J} \beta_j F_{ij} + \sum_{k}^{K} s_k(D_{ik}) + s_l(X_i, Y_i) \right)$$

where $log(a_i)$ is an offset term that corresponded to the area of each segment ($a_i = 2wl_i$ where w is the total strip width and l_i is length for segment i), β_0 is an intercept, $\beta_j F_{ij}$ represent factor terms (e.g., season) with β_j representing the regression coefficients for factor variable F_j, $s_k(D_{ik})$ represent one dimensional smooth terms (e.g., depth) implemented using quadratic *B*-splines with flexibility chosen using spatially adaptive smoothing (SALSA) methods (Walker et al. 2010) with 1–3 knt specified and a starting point of 2 knt, and $s_l(X_i, Y_i)$ represents a two-dimensional smooth term of location (determined for each segment i by X_i and Y_i).

The models were fitted using the complex region spatial smoother (CreSS; Scott-Hayward, Mackenzie, et al. 2014) with SALSA for model selection (Walker et al. 2010) implemented using the MRSea package v1.6 (Scott-Hayward, Oedekoven, et al. 2014) in R (R Core Team 2024). Standard errors were calculated taking account of any correlation in the residuals along the transects.

2.3.1.3 | Model Specification. For spatial modeling, location, season, and depth were considered as explanatory variables. Location of the segment, measured as a distance (km) east (X) and north (Y) from a reference point (76.0°W, 34.2°N; chosen so that all distances would be positive from this point), was fitted as a 2-dimensional term. Months (when the survey took place) were combined to create seasons based on average coldest and warmest *SST* and were defined as winter (January to March), spring (April to June), summer (July to September), and fall (October to December). Detected numbers were small in summer and fall, so these two seasons were combined creating a factor with 3 levels (*Season*3). Year was fitted as a factor variable with 9 levels (*Year*). The variables *depth* and *SST* were fitted as 1-dimensional smooth terms. Distance to coast was correlated with X, therefore it was not considered in the spatial modeling. The variables *depth* and *shelf* were also closely related and therefore only one of these variables at a time was included in a model. Location was included in all models and included an interaction with *Season*3. An interaction between *Year* and location could not be fitted because there were too few sightings in some years and not all the region of interest were covered each year, in particular, the surveys in 2017 to 2019 only took place in the north of the region.

Variable selection was implemented within the model fitting procedure so that (e.g., depth) could be linear, smooth, or removed (Scott-Hayward et al. 2022). The QBIC (Quasi-likelihood Bayesian Information Criterion) was used to compare models and the model with the lowest QBIC was selected (Table S4). For the selected model, diagnostics were performed to ensure model assumptions were valid (e.g., checking residuals for systematic patterns).

2.3.1.4 | Estimating Abundance and 95% Confidence Intervals. Using the selected model, predicted abundance was calculated for a grid of points (the prediction grid), with associated area and known values for the explanatory variables, throughout the region of interest. Since *SST* changes spatially and temporally, an average *SST* was obtained for each grid point for each season using the *SST* for the 15th day of each month (in the season) from years 2011 to 2019, inclusive (S6).

Relative abundance was estimated by summing predicted abundance over all grid points in the study area. The confidence intervals for total abundance were obtained from a parametric bootstrap procedure available in MRSea (Scott-Hayward, Oedekoven, et al. 2014); 1000 bootstrap replicates were generated to build a distribution of abundance estimates for the combined study area. To account for the uncertainty in both the detection function and the spatial surface, the coefficient of variation from the distribution of abundance estimates was combined with the coefficient of variation of the detection function using the delta method to obtain an overall coefficient of variation; 95% log-normal confidence intervals (CIs, Buckland et al. 2001) were then obtained for overall abundance in each season. A similar parametric bootstrap procedure was used to assess the variation in the estimated density surfaces.

2.3.2 | Conventional Distance Sampling Abundance Estimates

Conventional distance sampling abundance estimates (Buckland et al. 2001) provided estimates of species groups (all species combined and endangered species) and one individual species (fin whales). It is important to note that this approach to obtaining seasonal abundance estimates assumes that density is the same throughout the survey region for each season, and these design-based estimates should be treated with caution given the unequal survey coverage within the study region.

Abundance (N) for each season was estimated as follows:

$$\hat{N} = A.\frac{n \cdot \bar{s}}{2wL\hat{P}_a}$$

where A is the area of the region of interest, 32,800 km^2. n in the number of detected groups within w, $\bar{s}$ is average group size, w is the truncation half-width of the strip, 1800 m, L is total length of search effort, and $\hat{P}_a$is the average probability of detection in the covered region of area $2wL$.

These analyses were undertaken using the mrds package (Laake et al. 2019) in R (R Core Team 2024). Estimated abundance over all seasons was an average of seasonal abundance weighted by search effort.

2.4 | Qualitative Assessment of Occurrence and Distribution (2001–2019)

To determine whether the seasonal patterns of occurrence observed in the spatial models were representative of sightings from the full period of the study, we calculated sighting rates (total number of on-effort sightings recorded per 100 km flown) from all three aerial surveys for each species and season.

We also took advantage of the full suite of available data, from all on- and off-effort sightings from aerial surveys, all sightings from vessel cruises and all stranding records collected between 2001 and 2019, to more comprehensively explore how each species utilized the study area. We calculated the total numbers of baleen whales (best estimate of all individuals) documented from each platform (aerial, vessel, and stranding) and for each species. Geographic positions of whale sightings (aerial and vessel) and strandings were plotted using ArcGIS Version 10.1 (ESRI 2011).

A question that has arisen in the context of interpreting patterns from stranding data is whether these records reflect the live species assemblage within a given area (Pyenson 2011). To assess this question within our study area, we calculated Dead:Live (D:L) ratios (Stranding: "Aerial" Sighting) based on Pyenson (2011; see his Table 2) for each species. The Strand:Aerial (Dead:Live) ratio provided a metric to determine whether more individuals of one species stranded than were observed during surveys or if more individuals were observed during surveys than stranded.

3 | Results

3.1 | Spatial Density Modeling and Abundance (Aerial Surveys 2011–2019)

Baleen whale density and abundance varied spatially and by season. Perpendicular distances were truncated at 1800 m (Figure 2), leaving 115 groups of baleen whales included in the modeling efforts. The half-normal detection function was selected (Figure 2) and the estimated average probability of detection was 0.51 (coefficient of variation (CV) = 0.07). The largest number of baleen whales (all species combined) estimated to be present in a single segment was 29 (during the month of February) but 99% of effort segments did not contain any sightings (Figures S3 and S4). The selected model (see Table S4) included terms for *Season*3 and an interaction term between location and *Season*3.

Abundance estimates for each season were generated from the spatial model; estimated abundance of all baleen whales was highest in winter (94; 95% confidence interval (CI) = 50–176) and spring (32; 95% CI = 18–56), and lowest in summer/fall (9; 95% CI = 5–17). The area of highest density was north of 36° N, with high densities particularly concentrated in the northern section of the study area in spring (Figure 3). There was substantial uncertainty associated with the density surfaces, but it should be noted that small, estimated values can inflate coefficients of variation and result in highly uncertain estimates (Figure 3).

Abundances were also estimated using conventional distance sampling methods (Buckland et al. 2001) for all species combined (fin, humpback, NARW, minke and sei whales, excluding blue whales), endangered whales (fin, NARW and sei whales), and fin whales (Table 1). The seasonal pattern in abundance between the two approaches was similar—more baleen whales in cooler months (winter/spring) and fewer in summer and fall (Table 1; Figure 3).

3.2 | Qualitative Assessment of Whale Records (2001–2019)

To offer a more comprehensive view of species occurrence, sighting and stranding data collected over the entire 18-year period (2001–2019) were used to qualitatively assess seasonal

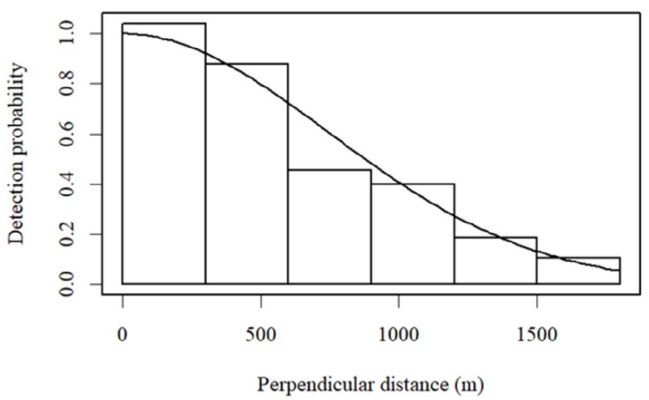

FIGURE 2 | Estimated detection function overlaid onto the scaled histogram of perpendicular distances for large whales recorded during aerial surveys (on effort) within the study area (except the single blue whale sighting) between 2011 and 2019. All species are assumed to have had the same detection probability. The half-normal form of the detection function was used to model detections because it had a lower Akaike Information Criterion (AIC) value than the hazard rate (1674 vs. 1677, respectively).

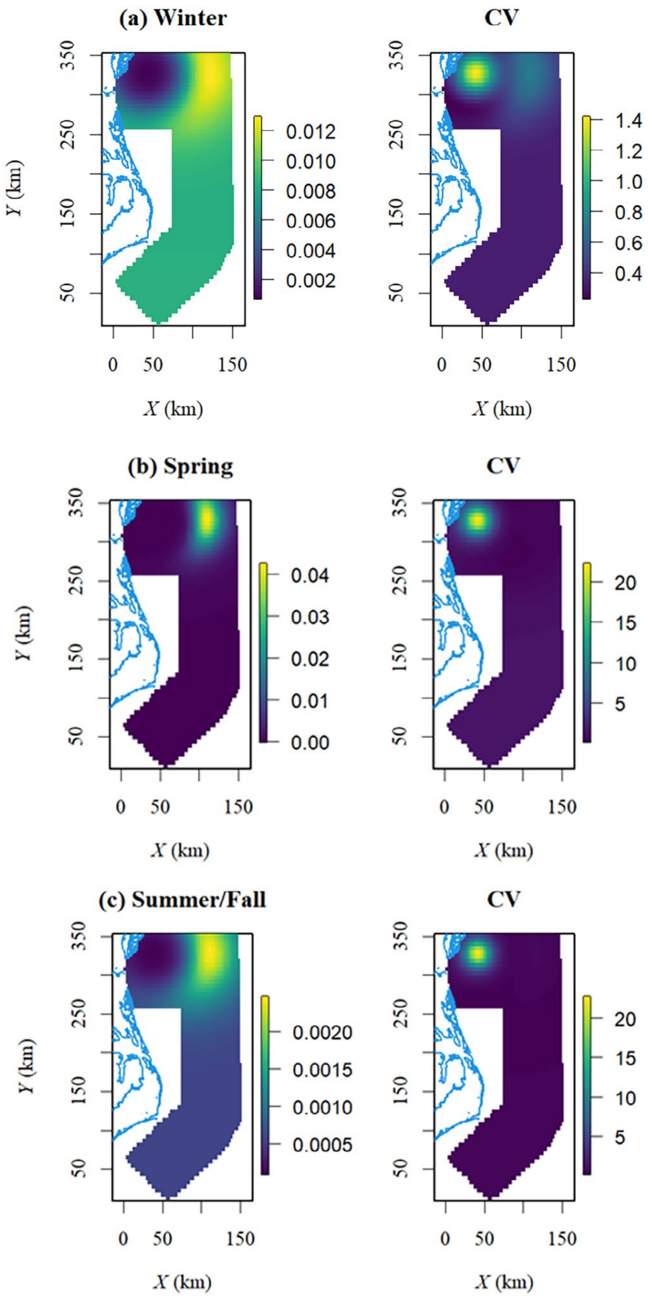

FIGURE 3 | Density estimates by season (whales/km^2, left) and coefficient of variation (*CV*, right) for all large whale species combined, for (a): Winter, (b): Spring, (c): Summer/fall. Scales differ for each plot. These density maps include only on-effort sightings data generated during aerial surveys between 2011 and 2019, with survey areas shown in Figure 1b,c. The white area along the coast of North Carolina reflects no survey effort.

occurrence and distribution of each species. Data from the three platforms were used as appropriate based on the goal of the assessment. The data sets used are defined in each section. For example, on-effort aerial survey data were used to calculate seasonal sighting rates while photo-ID data from all platforms and stranding data were used to describe demographics.

During the study period of 2001–2019, a total of six baleen whale species—humpback, fin, NARW, minke, sei, and blue (listed in order of their total number of sightings)—were detected across survey platforms and in the stranding record (Table 2; Figure 4). Forty-five percent ($n = 376$) of all baleen whales were documented from aerial surveys, 38% ($n = 316$) from vessel cruises, and 17% ($n = 146$) from stranding records (Table 2). Including all data sets, humpback whales accounted for 60% ($n = 503$) of all baleen whales in this study, followed by fin (24%; $n = 197$), NARW (9%; $n = 76$), minke (6%; $n = 51$), sei (1%; $n = 10$), and a single blue whale (Table 2; Figure 4). Vessel surveys were focused on documenting humpback whales, but this species also displayed the highest stranding number and was the second most frequently sighted species during aerial surveys.

3.2.1 | Seasonal Occurrence and Distribution (2001–2019)

Across seasons, sighting rates (which standardizes the differing levels of aerial survey effort between seasons) were highest for fin, humpback, and NARWs, and lowest for minke, sei, and blue whales, respectively (Table 3). Similar to modeled abundance estimates, sighting rates for all species combined were highest in winter (54%), followed by spring (32%), summer (8%), and fall (5%; see Tables 1 and 3). Humpback whales displayed the highest sighting rate in winter and fall, and fin whales had the highest sighting rate in spring. NARWs were observed in all seasons except summer, and minke and fin whales were the only species observed across all seasons (Table 3; Figure 5).

3.2.2 | Environmental Covariates

Including both on- and off-effort aerial survey sightings (2001–2019) increased the number of records available to assess species distributions relative to corresponding environmental data within the study area. All baleen whales with available environmental data were located between 0.8 and 138.3 km from the nearest coastline ($n = 246$; mean $= 53.4 \pm 38.5$ km) and documented in water depth ranging from 1.9 to 3093.2 m ($n = 238$; mean $= 193.4 \pm 531.2$ m). Aerial survey data revealed 72% of all humpback whale sightings were within 50 km of the nearest coastline, while 79% of fin whales and all minke and sei whales were distributed greater than 50 km from the coast (Table 4). Ninety percent (53 of 59) of individual NARWs were outside of the currently designated Seasonal Management Areas (SMAs; Figure 4c). Each of the NARW sightings occurred between December and April, which is within the period of time the SMA is active. Species sightings shared broadly overlapping water temperatures; all baleen whales ($n = 148$) were sighted in waters with sea surface temperatures (*SST*) between 3.2°C and 29.9°C (mean $= 13.3°C \pm 6.8°C$). See Table 4 for information on distribution of each species relative to distance from the coast, depth and *SST*.

3.2.3 | Stranding Records and Life History

Records of stranded baleen whales provided insight into the seasonality of stranding patterns (Figures 5 and 6) and the sex and total length provided information on the demographics

TABLE 1 | Abundance estimates using conventional distance sampling methods were calculated by season and overall (Total) based on aerial survey sightings (on effort) recorded between 2011 and 2019 for: (a) all species combined except blue whale (i.e., fin, humpback, NARW minke and sei whales), (b) endangered whales (fin, NARW and sei whales) and (c) fin whales.

(a) All species combined (except blue whale)									
Season	***L***	***n***	**ER**	**CV.ER**	***s***	**CV.*s***	***N***	**CV.*N***	**95% CI**
Winter	23,360.41	44	0.00188	0.19	2.25	0.17	76	0.29	44–133
Spring	34,093.15	50	0.00147	0.22	1.52	0.11	40	0.27	24–67
Summer	26,452.33	13	0.00049	0.31	1.15	0.08	10	0.34	5–19
Fall	21,319.97	8	0.00038	0.43	1.37	0.26	9	0.47	4–22
Total	1,05,225.86	115	0.0011	0.13	1.78	0.11	34	0.19	24–49
(b) Endangered whales									
Season	***L***	***n***	**ER**	**CV.ER**	***s***	**CV.*s***	***N***	**CV.*N***	**95% CI**
Winter	23,360.41	24	1.00E-03	0.26	2.37	0.3	44	0.42	20–97
Spring	34,093.15	33	9.70E-04	0.26	1.61	0.1	28	0.28	16–48
Summer	26,452.33	9	3.40E-04	0.37	1.22	0.1	7	0.4	3–15
Fall	21,319.97	2	9.40E-05	0.71	2.5	0.4	4	0.83	1–17
Total	1,05,225.86	68	6.50E-04	0.16	1.91	0.2	21	0.24	13–33
(c) Fin whales									
Season	***L***	***n***	**ER**	**CV.ER**	***s***	**CV.s**	***N***	**CV.*N***	**95% CI**
Winter	23,360.41	18	7.70E-04	0.32	2.67	0.29	37	0.49	15–92
Spring	34,093.15	27	7.90E-04	0.28	1.48	0.09	21	0.27	12–35
Summer	26,452.33	9	3.40E-04	0.37	1.22	0.1	7	0.4	3–15
Fall	21,319.97	2	9.40E-05	0.71	2.5	0.43	4	0.83	1–17
Total	1,05,225.86	56	5.30E-04	0.18	1.94	0.18	18	0.26	11–30

Note: Search effort (*L*, km), number of groups (*n*) within the truncation distance (*w*), encounter rate (ER; groups/km) and CV (CV.ER), average group size (*s*) and CV (CV.*s*), estimated abundance of individuals (*N*) and CV (CV.*N*), and 95% Confidence Intervals (CI) are reported. Total abundance is the average abundance over all seasons, weighted by search effort.

TABLE 2 | Number of whales of each species (based upon best estimate counts of individuals in a sighting) documented from all datasets, including aerial survey (both on- and off-effort sightings), vessel cruises, and records of stranded whales off the coasts of Virginia and North Carolina between 2001 and 2019.

	Humpback	**Fin**	**NARW**	**Minke**	**Sei**	**Blue**	**Total**
Aerial	137	153	59	22	4	1	376
Vessel	274	35	4	3	0	0	316
Stranded	92	9	13	26	6	0	146
Total	503	197	76	51	10	1	838

of individual whales within the study area (Table 6). The D:L ratio demonstrated that all species recorded during visual surveys, with the exception of the blue whale, were recorded in the stranding record (Table 5). Species prevalence between the sighting and stranding records differed across seasons (Figure 6). For example, while the fin whale was one of the most commonly sighted species across all seasons, this species stranded relatively infrequently; the opposite was true for minke whales, which had the highest number of strandings during spring and fall when there were relatively few sightings (Figure 6). Twice the number of sei whales stranded ($n = 6$) compared to live sightings (3 sightings totaling 4 individuals). The bulk of sei whale strandings were in winter, a season when no live sightings were documented even though most survey effort occurred in winter (Figure 6).

The sex and total length (TL) could be confirmed for 93 individual stranded baleen whales (Table 6). Humpback whales were predominately juvenile (and also had the smallest SD in mean TL). NARWs ranged from calves (exclusively male) to near-term,

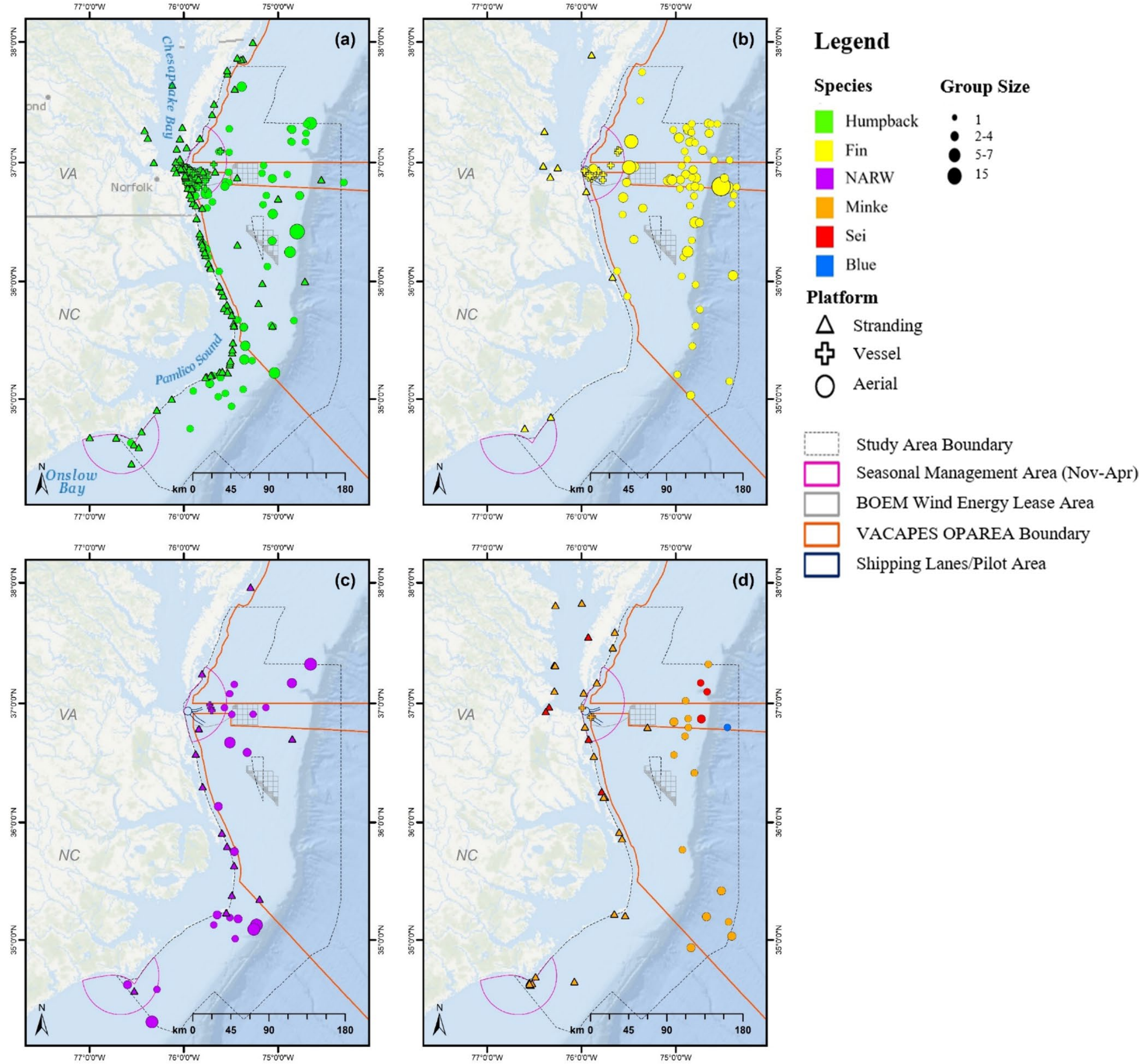

FIGURE 4 | Occurrence and distribution of baleen whales between 2001 and 2019. Sightings [on-effort aerial sightings (circles) and vessel (crosses)] and strandings (triangles) are plotted by species, including: (a) humpback (*Megaptera novaeangliae*) (note overlap of sightings and strandings near Chesapeake Bay mouth), (b) fin (*Balaenoptera physalus*), (c) North Atlantic right w hale (*Eubalaena glacialis*; NARW), (d) common minke (*B. acutorostrata*; orange), sei (*B. borealis*; red), and blue (*B. musculus*; blue) whales recorded in the combined NC and VA survey area. Aerial survey sightings are plotted by group size and range from 1 to 15.

pregnant females (see Table S3). Both male and female minke whales stranded as calves and mature animals. At least a subset of fin, minke, and sei whales were immature.

Stomach contents of stranded individuals were examined opportunistically and included both prey items and marine debris. For stranded humpback whales, intact fish, partially digested fish, fish bones, and otoliths from fish in the Family Engraulidae, the anchovies and Atlantic Menhaden (*Brevoortia tyrannus*; Virginia Aquarium Stranding Response Program [VAQS], unpublished data) were recorded. Marine debris (specifically rigid plastic) was found in the gastrointestinal tract of two sei whales, including a fractured DVD case with sharp edges that resulted in ulcerations of the stomach lining and the emaciated body condition of a 1397-cm female (VAQS, unpublished data).

3.2.4 | Opportunistic Observations

During both aerial and vessel surveys, all species except minke and sei whales were observed feeding. Humpback whales and NARWs were the species most commonly observed feeding. Humpback whales exhibited both lunge and bubble net feeding. NARWs were observed swimming subsurface with their mouths open, behavior consistent with feeding. Fin whales

TABLE 3 | Baleen whale species documented during aerial surveys off the coasts of Virginia and North Carolina between 2001 and 2019. Each column lists total number of on-effort sightings and (sightings per 100 km of survey effort).

Season	Effort (km flown)	Humpback whales/100 km effort	Fin whales/100 km effort	NARWs/100 km effort	Minke whales/100 km effort	Sei whales/100 km effort	Blue whales/100 km effort	All whales/100 km effort
Winter	64,365	40 (0.062)	33 (0.051)	16 (0.025)	6 (0.009)	0 (0.000)	1 (0.002)	96 (0.149)
Spring	63,241	15 (0.024)	31 (0.049)	5 (0.008)	3 (0.005)	3 (0.005)	0 (0.000)	57 (0.090)
Summer	26,452	0 (0.000)	10 (0.038)	0 (0.000)	5 (0.019)	0 (0.000)	0 (0.000)	15 (0.057)
Fall	39,735	6 (0.015)	1 (0.003)	1 (0.003)	1 (0.003)	0 (0.000)	0 (0.000)	9 (0.023)
All Seasons	1,93,794	61 (0.031)	75 (0.039)	22 (0.011)	15 (0.008)	3 (0.002)	1 (0.001)	177 (0.091)

were observed lunge feeding, defecating, and rolling at the surface. Additionally, surface-active groups (Cotter 2019; Parks et al. 2007) and nursing NARW calves (verified by New England Aquarium through photo-documentation records) were documented.

3.2.5 | NARW Photo-Identification

Based on sighting and stranding records from Virginia and North Carolina between 2001 and 2019, 81 individual NARWs were uniquely identified through photo-ID and matched to the North Atlantic Right Whale Consortium Identification Database (Right Whale Consortium 2021). Five individuals were re-sighted more than once in the study area (see Table S3) for sighting histories and demographics of known NARWs documented during this study. The sex was verified for 75 known individuals (Right Whale Consortium 2024). Fewer female NARWs ($n = 27$) were recorded during surveys compared to males ($n = 36$), while two more female whales ($n = 7$) stranded compared to males ($n = 5$). All known-aged calves were male ($n = 9$; Table S3; Right Whale Consortium 2021). Two pregnant females were documented from the stranding record (EGNo 1004 and EGNo 1909). Including calves of unknown sex, eight live calves were documented within the study area during aerial surveys and three as stranded specimens. A majority of records of calves were documented in March ($n = 6$), followed by December ($n = 2$), while single records of calves were recorded in February, April, and May (see Table S3).

4 | Discussion

This study utilized almost two decades of baleen whale presence data (survey and stranding records) to describe the occurrence of six species along the central mid-Atlantic coast, which is a region of extensive and increasing anthropogenic use. Between 2001 and 2019, a total of 838 baleen whales were sighted across multiple platforms off the Virginia and North Carolina coasts. Baleen whales were found year-round, with the highest estimated abundance and sighting rates of all species occurring during cool water months (winter/spring).

Aerial survey effort was skewed toward cool water seasons, whereas stranding records were continuously collected regardless of season. Winter (33.2% of total aerial survey effort) and spring (32.6%) had the highest aerial survey effort while fall (20.5%) and summer (13.7%) had lower survey effort. Spatial models and sighting rates that accounted for survey effort demonstrated species-specific differences in seasonal occurrence and distribution (Tables 1 and 3; Figures 3 and 5).

Given the extensive multi-institutional research efforts to study individual NARWs, we had the added benefit of gaining demographic information and sighting histories of individuals, adding to our understanding of how this critically endangered species utilizes the coasts of Virginia and North Carolina. These studies provide an important time series of data to guide management considering the extensive anthropogenic activities within the study area.

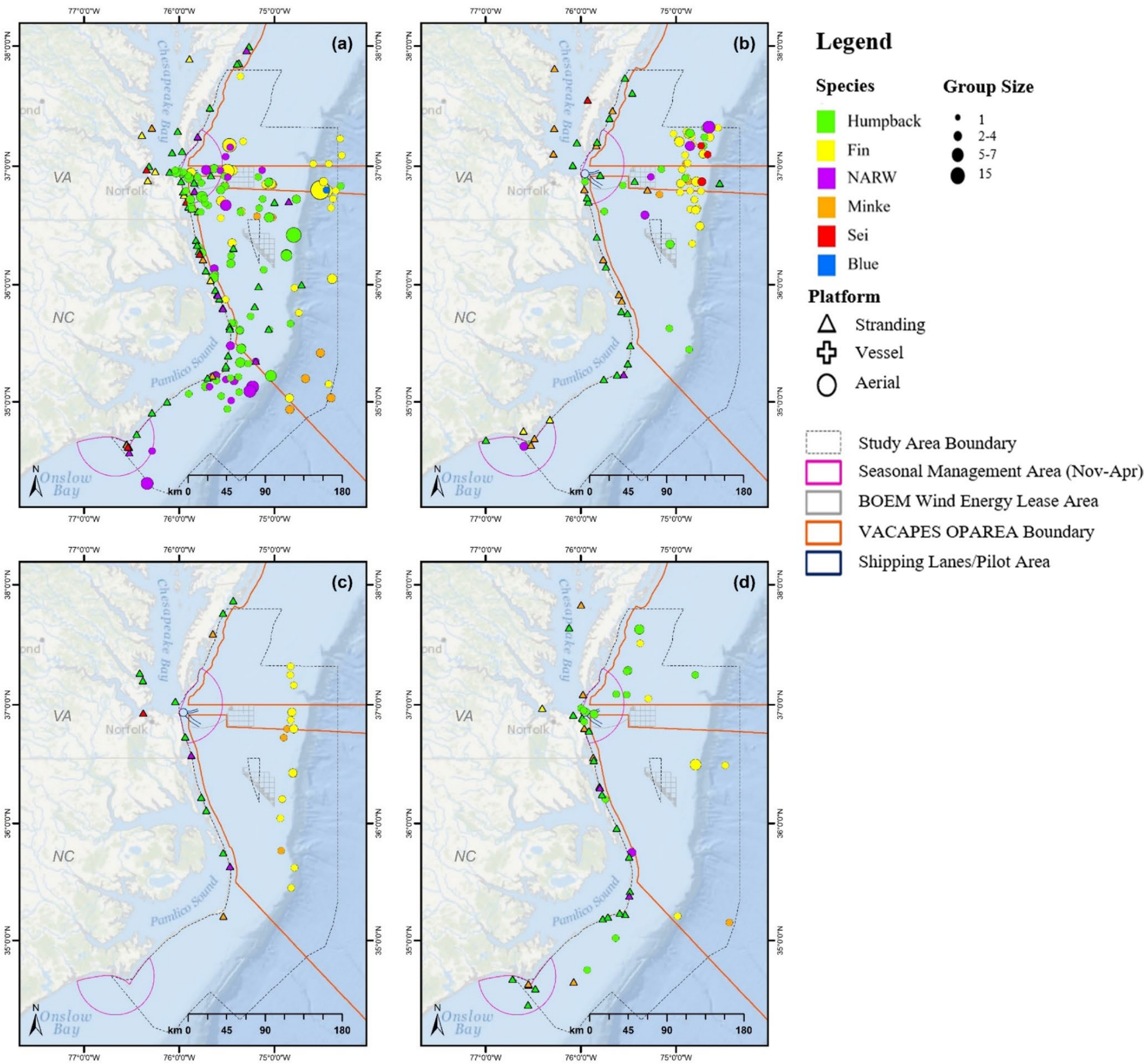

FIGURE 5 | Seasonal sightings (on-effort from aerial surveys; circles) and distribution of strandings (triangles) for baleen whales in the study area between 2001 and 2019. Seasons are defined as: (a) winter (January–March); (b) spring (April–June); (c) summer (July–September); and (d) fall (October–December). Species observed include humpback (green), fin (yellow), NARW (magenta), common minke (orange), sei (red), and a blue whale (blue). Aerial survey sightings are plotted by group size (range: 1–15 whales).

4.1 | Seasonal Patterns of Occurrence

The spatial modeling and abundance estimates, which utilized data from the most recent aerial surveys (2011–2019), indicated that whale density and distribution changed seasonally. All baleen whale species combined, endangered baleen whale species, and fin whales separately (for which sufficient sightings existed to estimate density) were most abundant in winter and spring; densities were lower in fall and summer. A similar seasonal pattern for fin, humpback, and NARWs was observed when sighting rates of on-effort aerial survey (2001–2019) data were compared. These results support findings from habitat-based density models (Roberts et al. 2016), the AMAPPS surveys (Palka et al. 2017), and acoustic studies in the proximity of the Virginia Wind Energy Area (Salisbury et al. 2019). Across seasons, the highest average densities occurred north of Cape Hatteras, NC (Figure 3), which coincides with the convergence zone of warm Gulf Stream waters flowing north and compression of the southerly flowing, cold, nutrient-rich waters of the Labrador Current (Figures 3 and 5).

Both humpback whales and NARWs were sighted relatively close to shore in winter, co-occurring with an area of high intensity vessel traffic at the mouth of the Chesapeake Bay (Figure 5a). In spring, whale sightings were clustered between 36°50 and 37°50 North, just inshore of the 100-m isobath (Figure 5b). The lower estimated abundances in fall and

TABLE 4 | Summary of geo-referenced environmental variable values that were available for associated aerial survey on- and off-effort sightings of each species documented in the study area between 2001 and 2019, including distance from coast (kilometers, km), depth (meters, m), and Sea Surface Temperature [SST, °Celsius (°C)]. These environmental covariates were acquired for geo-referenced baleen whale sightings and annotated using the Env-DATA System on Movebank (movebank.org; Dodge et al. 2013).

	Distance from coast (km)				Depth (m)				Sea surface temperature (°C)			
	n	**Range**	**Mean**	**SD**	***n***	**Range**	**Mean**	**SD**	***n***	**Range**	**Mean**	**SD**
Humpback	105	1.3–138.3	32	32.9	102	1.9–162.0	32.8	24.9	66	3.2–22.2	10.2	4.3
Fin	91	5.2–136.6	77.4	31.1	87	6.0–1933.7	290.3	553.3	54	6.2–29.9	16	7.4
NARW	27	0.8–86.5	27.4	23.8	27	5.6–77.4	29.5	22	11	6.2–21.6	11.2	4.9
Minke	19	50.9–104.5	82.9	13.7	18	3.0–3093.2	805.4	1265.70	15	8.8–28.1	19.2	7.3
Sei	3	87.2–102.5	95.3	7.7	3	81.5–268.8	144.7	107.5	2	8.9–9.2	9	0.2
Blue	1	128.2	128.2	—	1	1706.6	1706.6	—	0	—	—	—
All whales	246	0.8–138.3	53.4	38.5	238	1.9–3093.2	193.4	531.2	148	3.2–29.9	13.3	6.8

Note: Distance to the nearest coastline (0.04° resolution) was acquired for each geo-referenced sighting location (NASA 2020). Bathymetric data in meters were collected from NOAA National Geophysical Data Center using the ETOPO1, 1 Arc-Minute Global Relief Model (ETOP01, 2009). *SST* (°C); (8-day daytime average, 4-km resolution) was collected from the MODIS Ocean data set (MODIS: NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group).

summer for all baleen whales combined supports findings of fewer detections from acoustic studies (Salisbury et al. 2019) and coincides with the timeframe when most baleen whales are thought to be in their northern feeding grounds (e.g., Baumgartner and Mate 2005; Katona and Beard 1990; Kenney et al. 1995). In summer, the highest sighting rate was recorded for fin whales (Table 3, Figure 5c), a timeframe when this species is generally most abundant in waters off the northeastern U.S. (Palka 2020).

Observations of humpback whales within the study area were most commonly recorded in winter, a time when this species is known to migrate to low-latitude mating and calving areas (Katona and Beard 1990; Kennedy et al. 2013; Palsbøll et al. 1997), while acoustic studies within the region indicate near year-round presence peaking between fall and spring months (Davis et al. 2020; Whitt et al. 2015; Zeh et al. 2024). The total length of stranded whales and findings from photo-ID studies indicate that the humpback whales recorded within the study area are mostly juvenile whales (Aschettino et al. 2020; Barco et al. 2002; Swingle et al. 1993). Frequent observations of feeding were recorded during this study and have also been reported previously within the same area (Aschettino et al. 2020; Swingle et al. 1993). The presence of intact prey in the gastrointestinal tracts of stranded animals suggests at least some whales were feeding recently and prior to death, supporting findings of winter foraging for mostly juvenile humpback whales (Aschettino et al. 2020; Barco et al. 2002; Swingle et al. 1993).

Fin whale sightings occurred in all seasons, mostly along the continental shelf and inner slope and almost all occurrence records were north of Cape Hatteras, North Carolina. This more northerly distribution of fin whales agrees with findings from Davis et al. (2020) and Muirhead et al. (2018), who reported year-round acoustic detections in the mid-Atlantic and north to eastern Greenland, with fewer acoustic detections in the southeast U.S. The broadscale distribution of fin whales in the Exclusive Economic Zone from Cape Hatteras north along the western Atlantic (Edwards et al. 2015; Davis et al. 2020) and year-round presence in mid-Atlantic waters may lend support for seasonal movement (Silva et al. 2013) on a smaller scale than other baleen whale species, as has been suggested for fin whales in the north Pacific Ocean (Oleson et al. 2014). Within the study area, fin whales displayed the highest sighting rate overall during aerial surveys supporting broader scale seasonal modeling results for fin whale density along the east coast (Roberts et al. 2016). There was also a considerable number of fin whale sightings within the shipping lanes and SMA off Virginia.

NARWs were observed in the winter and spring seasons near shore in the central continental shelf region of the study area (Figures 4c and 5), which is similar to findings from aerial surveys off the New York Bight (Zoidis et al. 2021). The SMAs were designated to protect NARWs and the reduction of vessel speed has been shown to reduce mortalities resulting from vessel interactions (Conn and Silber 2013; 2014; Laist et al. 2014; Silber et al. 2014; Vanderlaan and Taggart 2007; Wiley et al. 2011, but see Van Der Hoop et al. 2013). It is important to note, though, that 90% of NARWs (53 of 59) in the present study were located outside of the designated SMA during the months of December through April, the timeframe during which the SMA is active.

Acoustic studies have detected NARWs during all months of the year in the mid-Atlantic (Davis et al. 2017; Whitt et al. 2013), including waters off the Virginia coast (Salisbury et al. 2019). During summer NARWs were not visually observed, and are commonly found at higher latitudes, in the northeastern foraging area (i.e., the Grand Manan Basin in the Bay of Fundy, and Roseway Basin, south of Nova Scotia; Brown et al. 1995; Gaskin 1987; Stone et al. 1988) and more recently in the Gulf of St. Lawrence (Crowe et al. 2021). The highest number of visual detections from our study occurred in winter and spring months, coinciding with peak acoustic detections (November and April) off the coast of Virginia (Salisbury et al. 2019; Roberts et al. 2024). Thus, passive acoustic surveys, coupled with increased visual survey effort, could continue to provide greater resolution to

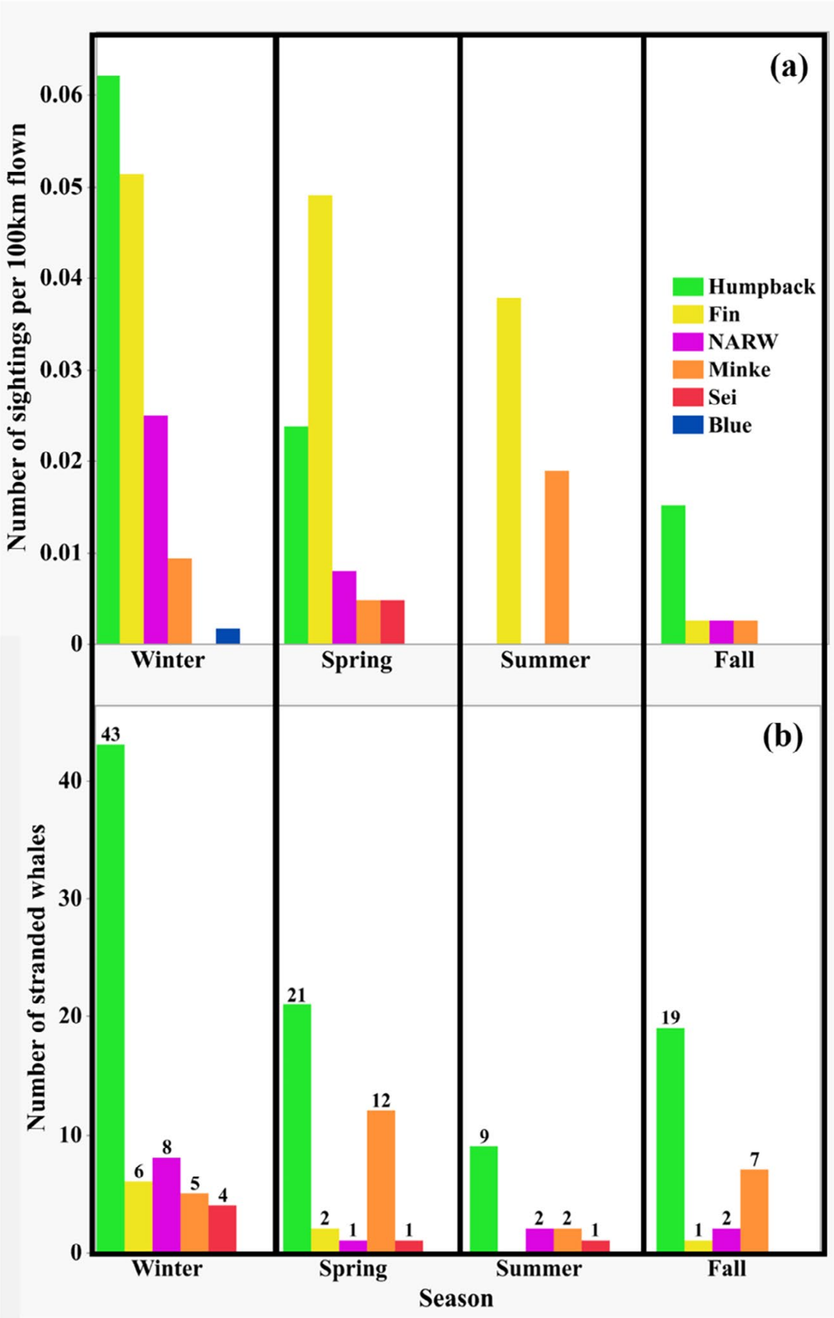

FIGURE 6 | (a) Seasonal sighting rates from aerial surveys [total number of on effort sightings recorded per 100 km (km) flown] of baleen whales in the combined NC/VA survey area between 2001 and 2019; (b) Total number of stranded whales ($n = 146$) of each species recorded during winter (January–March; $n = 66$), spring (April–June; $n = 37$), summer (July–September; $n = 14$), and fall (October–December; $n = 29$). Note differences in the rank orders of species between (a) sighting rates and (b) stranded records for each season JMP 2021.

seasonal occurrence of NARWs and other baleen whale species in this region (Davis et al. 2017, 2020; Roberts et al. 2024; Salisbury et al. 2019).

Fewer minke whales were observed as compared to other species documented in this study (Table 3; Figure 4), which is similar to the results from acoustic detections off Virginia (Salisbury et al. 2019). Sighting and detection rates could be lower for this species because of their relatively small size, low profile, and fast swimming/surfacing behavior and/or their generally offshore distribution. Minke whales in the western North Atlantic have displayed seasonal differences in movement, traveling closer to shore, along the continental shelf, during the northerly spring migration and further offshore during the southbound fall migration (Risch et al. 2014). Within the study area, the sighting rate was lowest for minke whales during fall, and there were fewer stranding records compared to spring. Such a pattern would be expected if more whales were offshore of the study area in fall and generally closer to shore in spring, lending support for the differential distribution during the northerly and southerly seasonal migration pattern of this species. Although numbers of minke whales were relatively low, seasonal detections within the study area offer useful insights into the distribution and migration of this species, which is otherwise limited in the western North Atlantic.

Although only a few records of sei whales were recorded in this study, these data are valuable to share given the limited information available for this species in the North Atlantic (Hayes et al. 2019; Mead 1977). Only in recent years were live sightings of sei whales documented within the study area (April 2018) and these sightings were located along the 100-m depth contour in the northern section of the study area (Figure 4d). Davis et al. (2020) analyzed baleen whale acoustic data collected between 2004 and 2014 in the western North Atlantic and found that sei whale detections were higher off the mid-Atlantic after 2010. The data presented here support these findings. Similar to findings from aerial surveys north of the study area (off the NY Bight), sei whales in this study were observed in spring and in offshore waters (Figure 5), although sightings were rare (Zoidis et al. 2021). Sei whale sightings from the Northeast and Southeast Fisheries Science Center's shipboard and aerial surveys since 1995 have all been north of 40° N (approximately the latitude of NJ/NY; Garrison et al. 2011; Hayes et al. 2019; Palka 2020), although it is important to keep in mind that positive identification of this species can be extremely difficult (Hayes et al. 2019; Mullin and Fulling 2004). Thus, the presence of this species in the southern limit of its range, as well as more recent live sightings, are noteworthy.

TABLE 5 | Total number of stranded (Strand) specimens and (on-effort) aerial sightings (Aerial) for each species of baleen whale observed in the study area between 2001 and 2019.

Species	Strand	Aerial	S:A (D:L)
Humpback	92	61	1.51
Fin	9	75	0.12
NARW	13	22	0.59
Minke	26	15	1.73
Sei	6	3	2.00
Blue	0	1	—

Note: The Strand:Aerial (S:A) or Dead:Alive (D:L) ratio will be greater than one if more individuals of that species stranded than were observed during surveys, equal to one if the numbers are equal between Strand versus Aerial, and less than one if more individuals were observed during surveys than stranded.

Only a single blue whale was observed in the northern section of the study area (10 Feb 2019; Engelhaupt et al. 2020). Telemetry data revealed blue whales off the coast of Virginia and North Carolina during January and February (Lesage et al. 2017). Acoustic studies (Muirhead et al. 2018; Nieukirk et al. 2012) and aerial surveys (Zoidis et al. 2021) have documented blue whales as far south as the New York Bight—detections that are considered rare (Sears et al. 1990). Davis et al. (2020) reported the absence of acoustic detections south of North Carolina. Together, these findings support the results from habitat-based density models produced for the U.S. east coast (Roberts et al. 2016) and suggest this species is rare in the mid-Atlantic.

Roberts et al. (2016) reported seven species of baleen whales in their review of the distribution of cetaceans in the Gulf of Mexico and in the waters of the western North Atlantic off the U.S. All species, with the exception of Bryde's whales (*Balaenoptera edeni*), were documented within the study area. Bryde's, sei and the recently described Rice's whales can be very difficult to identify confidently without genetic analyses, especially for those at sea, or stranded whales in an advanced state of decomposition (i.e., Bryde's-like whales; Rosel et al. 2021; Brownell et al. 2024). The spatial models developed by Roberts et al. (2016) predicted that Bryde's whales should occur as far north as Cape Hatteras, NC. However, in a recent review, Brownell et al. (2024) reported that species identification has not been confirmed for any stranding or sighting of 'Bryde's' whales along the Atlantic seaboard of the U.S. All previous standings of Bryde's-like whales along the U.S. east coast that have been examined genetically have been confirmed to be Rice's whale (*B. ricei*; Brownell et al. 2024). Therefore, genetic analyses of stranded Bryde's-like whales along the U.S. east coast is important for future modeling efforts and to better understand the frequency of occurrence of Rice's whales along the U.S. east coast.

4.2 | Comparisons of Dead and Live Records

All species observed during aerial surveys, with the exception of the single blue whale, were found stranded in the study area (Table 5). Across all seasons combined, humpback, minke, and

TABLE 6 | Summary of total length (TL) measurements (cm) of stranded specimens of known sex within the study area.

	Total			Females				Males			
Species	*n*	Mean	SD	*n*	TL Range	Mean	SD	*n*	TL range	Mean	SD
Humpback	54	942	154	27	693–1390	949	160	27	609–1250	934	149
Fin	7	1424	311	5	905–1798	1396	341	2	1271–1720	1496	317
Minke	18	486	152	10	374–720	548	131	8	284–720	409	147
NARW	8	1085	394	4	1200–1600	1418	171	4	495–975	753	197
Sei	6	1079	356	4	629–1397	1003	411	2	1060-1402	1231	242
Total	93	—	—	50	—	—	—	43	—	—	—

Note: Only specimens assigned Smithsonian Institution Codes (Geraci and Lounsbury 1993) of "fresh" to "moderate" states of decomposition were used to reduce error in TL estimates associated with decomposition state.

sei whales were over-represented as strandings, and fin and NARWs were under-represented. Pyenson (2011) calculated cetacean D:L ratios at seven different locations around the globe. He found that for coastlines spanning more than four degrees of latitude (or > 2000 km), the stranding records provided higher species richness compared to live sightings, while the opposite was true for shorter coastlines (Mandelbrot 1967). The survey area within the present study spans an approximately four-degree latitudinal gradient. Our results suggest that the stranding record is reflective of the live species assemblage within the study area.

The comparison of sighting rates to the total number of stranding records indicated species-specific differences in seasonal presence although the rank order of species records varied across seasons and between datasets (Figure 6). The greatest difference in species representation in sighting and stranding records occurred in summer: only two species (fin and minke) were sighted, whereas four species were recorded in the stranding data (i.e., humpback, NARW, minke, and sei whales; Figure 6) Further comparison of the differences in rank order between live and dead records may elucidate ecological questions, species-specific or life-history-class-related vulnerability relevant to management. For example, humpback and fin whales were more common within the study area during spring; however, humpback and minke whales may be at greater risk of stranding given that the latter two species had the highest number of strandings during spring (Figure 5). The opposite case appears to be true for fin whales, which have the highest sighting rate compared to other species, although few strandings ($n = 2$; Figure 6). While no sightings of sei whales were recorded in winter, this season exhibited the highest number of strandings of this species and interestingly 3 of the 6 stranded whales were located inshore, within the Chesapeake Bay, which is noteworthy for an offshore species (Figures 4d and 6).

Humpback whales were the most commonly documented species during visual surveys (aerial and vessel) and accounted for 63% of all baleen whale strandings ($n = 92$, Table 2). While the UME declared in 2016 has contributed to the elevated total stranding numbers for this species, humpback whales were the most commonly stranded whale in the study area prior to the UME (Figure S5). Based on photo-ID records, Barco et al. (2002) found evidence that some humpback whales returned to Virginia waters over multiple years and exhibited some level of seasonal residency. Additionally, these authors showed that at least a subset of whales have a Gulf of Maine feeding stock origin suggesting the coastal waters of the study area are an important area for this stock NOAA 2016. Investigating the trend in increased numbers of humpback whales using the mid-Atlantic (e.g., King et al. 2021; Wiley et al. 1995; 2003) will improve understanding of the status of the stocks using the area and help guide conservation.

The NARW is one of the world's most critically endangered baleen whale species with a population of less than 350 whales remaining (Cooke 2020; Pace et al. 2017). Thus, the 63 records from visual surveys (67 individuals according to individually identified whales from the photo-ID records; New England Aquarium; Table S3) and 13 dead whales (most attributed to anthropogenic mortality; Sharp et al. 2019; Table 2) merit serious attention for directing monitoring efforts and management action within the study area (Moore et al. 2021).

The differences in sighting versus stranding numbers (D:L ratio) could be related to behavioral ecology or demographics that impact risk of, for example, vessel strikes as has been shown for juvenile humpback whales off the coast of New York (Stepanuk et al. 2021). While whales are in the presence of vessels, their swimming and foraging behavior might influence the risk of interactions with vessels. For predominantly offshore-distributed species such as fin whales, there is less likelihood of vessel encounters, and/or there is less likelihood that a carcass would reach the coast to be recorded. Alternatively, for more coastally distributed species, such as humpbacks and NARWs, these species co-occur in areas where vessel traffic is highest, inevitably creating a greater risk of injury and mortality from vessels, and they are also more likely to wash ashore to be recorded or be reported by transiting vessels.

4.3 | Life History

The data collected during surveys and strandings investigations suggest that multiple life history classes of baleen whales visit the study area. For example, the mean TL of stranded female and male fin whales in this study was 14.0 and 15.0 m, respectively (Table 6). Mitchell (1974) reported the mean TL of fin whales at sexual maturity taken at the Blandford, Nova Scotia whaling station in the 1960s to be 17.7 m for females and 17.5 m for males. Although measurements were based on limited specimens, the TL of the available specimens suggest that immature fin whales represent a portion of the individuals that visit this region. NARW mother-calf pairs, stranded pregnant females and neonates have all been recorded north of the southeast U.S. Critical Habitat area, within the mid-Atlantic region (Sharp et al. 2019; Waring et al. 2016; Whitt et al. 2013), including off Virginia and North Carolina (records included in this study). Female and subadult NARWs are known to be particularly vulnerable to human impacts such as vessel strikes and entanglement (Knowlton and Kraus 2001; Rolland et al. 2016; van der Hoop et al. 2012), and within the study area 21 adult females and at least 19 subadults were documented in this study (see Table S3). On the other hand, the mean TL of humpback whales from stranding records reported here was 9.4 ± 1.5 m and the SD was the lowest compared to all other species (Table 6), providing further support that most humpback whales documented in these mid-Atlantic waters are juveniles/immature (Clapham and Mead 1999; Clapham et al. 1999; Swingle et al. 1993).

As with NARWs (Hamilton et al. 1998), humpback whale demographics have been shown to influence risk to injury and mortality, thus, the life history data presented here provide potentially important insights for management. Stepanuk et al. (2021) found that demographics (juvenile whales) and behavior (e.g., nearshore foraging) of humpback whales were correlated with increased instances of ship strikes off New York. The predominance of juvenile whales documented nearshore in the shipping channels and SMA at the entrance of the Chesapeake Bay (Aschettino et al. 2020), frequent observations of feeding and high numbers of stranding events, all suggest that humpback whales are at great risk of mortality in the region (Laist et al. 2001; Lammers et al. 2013; Neilson et al. 2012; Vanderlaan et al. 2009; Wiley et al. 1995).

Given the relatively small number of detections and quick surfacing intervals of minke whales, life history class determinations are difficult to make from live observations. Stranding records provide a useful snapshot into the demographics of at least a subset of minke whales within the study area. Based on stranding records for which sex was determined ($n = 18$), the mean TL of females (5.5 m) and males (4.1 m) suggests these whales were very young, as size at weaning has been estimated to be between 4.5 and 5.5 m (Table 6; Christensen 1981).

Considering the limited number of sightings, stranding records provided important information on life history of sei whales (mean TL = 10.8 ± 3.6 m) using the central mid-Atlantic coast (Table 6). In the North Atlantic, mean adult sei whale length is estimated to measure approximately 14 m (Lockyer 1976), suggesting at least a subset of the stranded whales in this study was immature.

Together these long-term sighting and stranding data sets provide an in-depth view of species occurrence and offer insight into potential vulnerabilities within the study area.

4.4 | Management and Monitoring Considerations

Baseline data on species occurrence is essential for understanding baleen whale habitat use, ocean planning, developing management strategies to reduce and mitigate threats to vulnerable species and to assess effectiveness of implemented measures (e.g., Chavez-Rosales et al. 2019; Moore et al. 2021; Roberts et al. 2016; van der Hoop et al. 2012). The coastal and offshore waters of Virginia and North Carolina are heavily utilized by the shipping and commercial fishing industries, U.S. military, and increasingly by the energy sector (e.g., wind energy and seismic geophysical exploration). Current levels of anthropogenic mortality pose a major conservation concern in the region, particularly for humpbacks and NARWs (NOAA 2026a, 2026b, 2026c; Hayes et al. 2021) and those especially vulnerable to vessel strikes and entanglement (i.e., female and subadult NARWs; Knowlton and Kraus 2001; van der Hoop et al. 2012).

The results of this study and recent telemetry studies (Aschettino et al. 2020) indicate baleen whales and vessels are more likely to co-occur (e.g., around the mouth of the Chesapeake Bay) during fall and winter. Detections of whales were highest inshore within the shipping lanes and the SMA in winter (Figure 5). Thus, management efforts to reduce interactions can be directed at these time periods. The Coastal Virginia Offshore Wind (CVOW) project currently operates under such restrictions (BOEM 2024; COPs) and this study supports the restrictions currently in place. The best available research should continue to be considered during the agency/developer consultation process for offshore energy development. For example, the timing of wind farm construction should continue to be restricted to periods less likely to cause disturbance or when the lowest numbers of endangered whales have been detected (summer, within the study area; CVOW LOA Final Rule; 89 FR 4370, n.d.).

The mid-Atlantic ocean waters serve as important seasonal habitat for baleen whales (e.g., Roberts et al. 2016). As evidenced by findings in this study and others within the study area (e.g., Aschettino et al. 2020; Cotter 2019; Engelhaupt et al. 2020), the waters off Virginia and North Carolina are not only a migratory corridor between feeding and breeding areas, but serve as seasonal foraging habitat (Hodge et al. 2015) for multiple species/stocks, and life history classes of baleen whales (Swingle et al. 1993; Whitt et al. 2013; Wiley et al. 1995). The use (potentially year-round) of nearshore and mid-shelf waters for feeding, migrating, and nursing by NARWs, as well as the presence of at least two pregnant females and 11 calves within the study area, highlights the urgent need to mitigate threats and prioritize conservation action in areas and times where this critically endangered species co-occurs with heavy anthropogenic use (e.g., Aschettino et al. 2020; Moore et al. 2021; van der Hoop et al. 2012).

Increased use of the study area by humpback, NARWs, and possibly sei whales highlights the importance of continued monitoring to understand the underlying drivers of these apparent shifts in habitat use. We do not fully understand the ecological mechanisms influencing the apparent shift of species, such as the humpback whale (Barco et al. 2002; Payne et al. 1990; Ramp et al. 2015; Swingle et al. 1993; Wiley et al. 1995; Davis et al. 2020) and NARW (Davis et al. 2017) into mid-Atlantic waters, but changes in phenology and shifts in cetacean distributions are being observed on a global scale (e.g., Benson and Trites 2002; Davis et al. 2020; Pace et al. 2017; Ramp et al. 2015; Record et al. 2019; Salvadeo et al. 2011; Smultea et al. 2012). The Gulf of Maine is the closest major feeding area for multiple whale species documented in the study area and it is experiencing rapid changes in oceanographic conditions (Pershing et al. 2015). The results of this study provide a baseline to investigate future changes in baleen whale occurrence and seasonal abundance. Continued surveys and research in the mid-Atlantic could extend the long-time series of existing data necessary to determine the implications of such changes on baleen whale occurrence within the region, including those related to increasing ocean temperatures, changes in prey distribution (Meyer-Gutbrod et al. 2021; Record et al. 2019; Staudinger et al. 2019) as well as the potential for long-term recruitment of humpback whales into the mid-Atlantic region. Continued long-term surveys would also offer comparative data for post-development monitoring in the Wind Energy Areas. The analyses conducted in this study offer a framework for long-term, quantifiable results for comparison over time. Additionally, given the relatively nearshore occurrence and accessibility to species such as humpback whales and NARWs, the study area serves as a strategic site for future research.

5 | Conclusions

This study adds to increasing streams of evidence suggesting that mid-Atlantic Ocean waters deserve attention as foraging and calving habitat in addition to its importance as a migratory corridor for multiple species of baleen whales. Reasons for this include potential year-round presence of critically endangered NARWs, direct observations of feeding by multiple species, and the presence of multiple age classes. Urgent management action is needed to address high-intensity anthropogenic use and elevated baleen whale mortality attributed to vessel strikes, entanglement, or both. The results presented here offer new information that can be used for ocean planning and mitigating anthropogenic impacts to baleen whales in a region inundated by heavy and increasing human use. Multi-platform survey data supplemented with stranding and photo-ID records provide a robust understanding of baleen whale occurrence and distribution off the central mid-Atlantic coast of the U.S. Stranding data effectively reflect the live species richness along the Virginia and North Carolina coasts, while seasonal differences in the stranding record could provide clues for assessing species vulnerability. A long-term monitoring program is needed to monitor changes in seasonal occurrence and habitat use over time in an area experiencing increasing anthropogenic pressures.

Author Contributions

Sarah D. Mallette: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft, writing – review and editing. **William A. McLellan:** conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization. **D. Ann Pabst:** conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review and editing. **M. Louise Burt:** conceptualization, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft, writing – review and editing. **Ryan J. McAlarney:** conceptualization, data curation, investigation, methodology, project administration, supervision, validation, visualization, writing – original draft. **Gwendolyn G. Lockhart:** conceptualization, data curation, investigation, methodology, validation, visualization, writing – review and editing. **Erin W. Cummings:** data curation, investigation, project administration, validation. **Joel T. Bell:** conceptualization, funding acquisition, methodology, project administration, resources, supervision, visualization, writing – review and editing. **Matthew B. Ogburn:** funding acquisition, investigation, resources, supervision, writing – review and editing. **Philip K. Hamilton:** data curation, formal analysis, investigation, validation, writing – review and editing. **Andrew J. Read:** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, visualization. **Robert L. Brownell Jr:** supervision, writing – original draft, writing – review and editing. **Tiffany F. Keenan:** data curation, investigation, writing – review and editing. **Len Thomas:** formal analysis, writing – review and editing. **Peter G. Fisher:** writing – review and editing. **Jackie Bort Thornton:** investigation, writing – review and editing. **Mark P. Cotter:** data curation, investigation, project administration, validation. **W. Mark Swingle:** conceptualization, funding acquisition, project administration, resources. **Susan G. Barco:** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, visualization, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Supplementary tables. **Table S2:** On- and off-effort aerial survey sightings/individuals of each species of baleen whale documented from all aerial surveys in this study between 2001 and 2019. **Table S3:** Sighting records of individual North Atlantic right whales (NARWs) documented in the study area between 2001–2019. "Sighting EGNo" represents the formal catalog number assigned to an individual NARW by New England Aquarium through the North Atlantic Right Whale Catalog. Note. EGNo with an asterisk denotes resighting of an individual whale. Sex was determined visually from photographs, through genetic samples or verified by both means. Age class determination is based upon photo-ID records. Intermatch code is the specimen ID reported by the institution of record. Primary contributor of a sighting record is listed by institution. UNCW=University of North Carolina Wilmington; VAQS=Virginia Aquarium Stranding Response Program; SI=Smithsonian Institution; VAQS/UNCW=Joint aerial surveys; HDR/A=HDR Inc. aerial surveys; HDR/V=HDR Inc. vessel surveys. **Table S4:** The QBIC scores for the fitted models; s() indicates a smooth term. The selected model is shown in bold font. **Figure S1:** Total search effort flown during aerial surveys in the combined NC/VA survey area between 2001 and 2019 (Total = 193,794 km). Data from 2011 to 2019 were used for abundance estimation. The complete aerial survey data set (2001–2019) was used to explore patterns of baleen whale occurrence and was complemented by vessel and stranding data where appropriate. **Figure S2:** Average seasonal sea surface temperature (*SST*; °C) for each season between 2011 and 2019 within the study area. **Figure S3:** Estimated numbers of baleen whales (fin, humpback, NARW, minke, and sei) combined detected while on-effort between 2011 and 2019 per segment by season. The size of the circle is proportional to the estimated number of individuals per segment; the maximum number is the number given in parentheses. The gray dots indicate the midpoints of the segments of the search effort. The dashed line is the 100-m contour, and the dotted line is the 2500-m contour. **Figure S4:** Estimated numbers of baleen whales (fin, humpback, NARW, minke, and sei) combined per segment by month. The size of the circle is proportional to the estimated number of individuals per segment; the maximum estimated number of whales in a segment for that month is given in parentheses. Only data from aerial surveys conducted between 2011 and 2019 are included. The gray dots indicate the midpoints of the segments of search effort. The dashed line is the 100-m contour and the dotted line is the 2500-m contour. **Figure S5:** Total number of stranded whales in each year between 2001 and 2019. The horizontal redline at the year 2016 for humpback and 2017 for both NARW and minke whales denotes the declared start of the respective Unusual Mortality Events.