



## Distribution and Abundance of Beaked Whales (Family Ziphiidae) Off Cape Hatteras, North Carolina, USA

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Complete List of Authors:	McLellan, William; UNC Wilmington, Biology & Marine Biology McAlarney, Ryan; UNCW, Biology and Marine Biology Cummings, Erin; UNC Wilmington, Biology and Marine Biology Read, Andrew; Duke University, ; Paxton, Charles; University of St Andrews, CREEM Bell, Joel; Naval Facilities Engineering Command Atlantic, Pabst, Ann; UNC Wilmington, Biology and Marine Biology
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**ABSTRACT**

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35 Beaked whales are vulnerable to the impacts of disturbance from several sources of  
36 anthropogenic sound. Here we report the distribution and abundance of beaked whales off Cape  
37 Hatteras, North Carolina, USA, an area utilized by the U.S. Navy for training exercises, and of  
38 particular interest for seismic geophysical surveys. From May 2011 through November 2015,  
39 monthly aerial surveys were conducted at the site. Beaked whales were encountered 74 times ( $n=$   
40 205 individuals) during these surveys. *Ziphius cavirostris*, the most commonly encountered  
41 species, was observed in every month of the year. *Mesoplodon* spp. were encountered in ten  
42 months of the year. Photographs of adult males with erupted teeth permitted six sightings to be  
43 identified conclusively as *M. europaeus*; *M. mirus* was also photographed just outside the study  
44 area. Beaked whale surface densities stratified by depth ( $0.005 - 0.007/\text{km}^2$ ) were among the  
45 highest reported in the world for small ziphiids. A quantitative comparison of sightings and  
46 stranding records suggests that strandings do not accurately reflect the relative abundance of  
47 beaked whale species in this area. We conclude that Cape Hatteras, at the convergence of the  
48 Labrador Current and Gulf Stream, is a particularly important year-round habitat for several  
49 species of beaked whales.

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51 **Keywords:** Beaked whales, Cape Hatteras, *Ziphius cavirostris*, *Mesoplodon europaeus*,  
52 *Mesoplodon mirus*, densities, strandings

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## INTRODUCTION

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Beaked whales (Family Ziphiidae) are found in deep water habitats worldwide, including submarine canyons (Hooker and Baird 1999*a, b*; Waring *et al.* 2001; D'Amico *et al.* 2009; Arcangeli *et al.* 2014), around oceanic islands (Baird *et al.* 2006; Tyack *et al.* 2006; Schorr *et al.* 2009, 2014) and the continental slope (Waring *et al.* 2001, Hamazaki 2002, Mullin and Fulling 2003). Beaked whales are a phylogenetically diverse family (22 species in six genera currently recognized by the Committee on Taxonomy of the Society for Marine Mammalogy), distributed throughout the world's oceans (reviewed by MacLeod *et al.* 2006), but these remain some of the most poorly understood species of large mammals.

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Recently, the extreme deep diving abilities of multiple species of beaked whales have been described through the use of digital archival tags and satellite-linked dive recorders (*e.g.*, Baird *et al.* 2006, Tyack *et al.* 2006, Schorr *et al.* 2014). *Ziphius cavirostris*, for example, can dive to 3,000 m and remain submerged for over two hours (Schorr *et al.* 2014). The deep foraging dive records of both *Z. cavirostris* and *Mesoplodon densirostris* are the longest and deepest of any air-breathing vertebrate (Tyack *et al.* 2006). Their long dive times, short surface durations, and inconspicuous behavior when surfacing, make beaked whales particularly cryptic (Barlow *et al.* 2006, Barlow 2015). In addition, although *Z. cavirostris* is relatively easy to identify at close range, most mesoplodonts are not, and neither group is readily distinguishable from a distance (Davis *et al.* 1998, Waring *et al.* 2001, Mullin and Fulling 2003, Aguilar de Soto *et al.* 2017). Due to these challenges, beaked whales are often managed as complexes of multiple species (*e.g.*, Waring *et al.* 2014).

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There is a growing need for more precise and specific information on the distribution and abundance of beaked whale species, as they are particularly vulnerable to certain sources of

81 anthropogenic acoustic disturbance (Tyack *et al.* 2011). Mass strandings of beaked whales have  
82 occurred in association with naval sonar exercises (reviewed in Cox *et al.* 2006) and possibly  
83 seismic survey activities (Taylor *et al.* 2004). Barlow *et al.* (2006) noted that better information  
84 on abundance and density is needed to evaluate the risks to, and mitigate potential impacts of,  
85 anthropogenic disturbance on beaked whales. Cox *et al.* (2006) suggest that this information is  
86 particularly needed in areas where such anthropogenic impacts are known to occur or are  
87 planned.

88 We conducted year-round aerial surveys off Cape Hatteras, NC, USA, from May 2011  
89 through November 2015, as part of an ongoing monitoring project of sites utilized by the U.S.  
90 Navy for training and testing activities in the Atlantic. The aim of the surveys was to provide  
91 data on all cetaceans, sea turtles, and vessel activity in the survey area. Here we present data on  
92 the spatial and temporal patterns of occurrence, density, and abundance of beaked whales in the  
93 study site. The waters off Cape Hatteras are used by the U.S. Navy for its Atlantic Fleet Training  
94 and Testing activities ([http://aftteis.com/Background/Navy-Training-and-Testing/Training-](http://aftteis.com/Background/Navy-Training-and-Testing/Training-Ranges)  
95 [Ranges](http://aftteis.com/Background/Navy-Training-and-Testing/Training-Ranges)) and have been included as an area of particular interest in permit applications for  
96 commercial seismic surveys (<http://www.nmfs.noaa.gov/pr/permits/incidental/oilgas.htm>).  
97 Stranding records can provide additional information on cetacean species diversity (Pyenson  
98 2011), so we also compared the beaked whale sighting data set from Cape Hatteras with  
99 cumulative stranding records for the state of North Carolina.

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## 104 METHODS

105 *Study area*

106 The study area consists of a 15,765 km<sup>2</sup> straddling the shelf break east of Cape Hatteras,  
107 North Carolina (Fig. 1). Twenty-six transect lines were placed perpendicular to the shelf break,  
108 ranging from 73.5 to 81.5 km in length and spaced ~8 km apart. Each transect extended from the  
109 continental shelf to abyssal (depth of approximately 2,500-3000 m) waters. The oceanography of  
110 the study area is dominated by the convergence of two large current systems – the cold,  
111 southward flowing Labrador Current and the warm, northbound Gulf Stream current – which  
112 meet near Cape Hatteras at 35.2N / -075.5W.

113 The southern limit of the study area is approximately 80 km north of Onslow Bay, North  
114 Carolina, a site surveyed by this team from June 2007 to June 2010 (see Read *et al.* 2014). The  
115 Onslow Bay site, originally identified by the U.S. Navy as the preferred site for construction of  
116 an Undersea Warfare Training Range (USWTR), was the focus of monthly aerial surveys  
117 identical to those utilized in the present study (described below). On three occasions surveys  
118 were extended beyond the 1,000 m isobath in Onslow Bay, to search for beaked whales, which  
119 were never observed within the core study area. Resulting sighting data of beaked whales from  
120 these offshore surveys in Onslow Bay are included in the spatial comparison of sightings and  
121 strandings (see below).

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## 123 Aerial surveys

124 Aerial surveys were conducted off Cape Hatteras from May 2011 through November  
125 2015 in a *Cessna 337 Skymaster* at an altitude of 305 m and a speed of 185 km/h, using methods  
126 similar to those outlined in Read *et al.* (2014). Surveys were conducted on days with low sea

127 states and optimal visibility. Although Beaufort Sea States encountered during surveys ranged  
128 from 0-5, effort was targeted to low sea states. Annual average Beaufort Sea States were 3.48  
129 (2011), 3.01 (2012), 2.44 (2013), 3.00 (2014), and 2.62 (2015). The goal was to complete a  
130 subset of 26 tracklines each month, although weather occasionally prevented this goal from  
131 being reached (Table 1). Total distance surveyed ranged from 149 km to 1,901 km per month.

132 During surveys, two experienced observers (i.e. each with at least 3 yr of small cetacean  
133 aerial survey experience), equipped with a GPS unit, data sheet and binoculars, monitored each  
134 side of the plane through a standard (not bubble) window. Each sighting was independent and  
135 analyzed with its own covariates. The observers recorded the start and end of transect lines, any  
136 changes in environmental variables (i.e. cloud cover, sea state, visibility, and glare), and  
137 sightings of marine mammals, sea turtles and vessels. When a cetacean sighting cue was  
138 observed, the observer took a GPS waypoint and measured the vertical sighting angle using fixed  
139 marks on the wing struts of the plane. Initial forward angle was also recorded to determine the  
140 observation window when animals can be seen at the surface (see availability calculations  
141 below). The aircraft then went off-effort, broke from the trackline and closed directly on the  
142 sighting, and a sighting waypoint was recorded. Thus, the distance from the trackline sighting  
143 cue and the position of the cetacean(s) (i.e. the distance between the two waypoints) could be  
144 calculated to provide an independent measure of distance of the sighting from the trackline. The  
145 plane circled over the sighting while obtaining photographs to confirm species identity and  
146 number of individuals.

147 During each encounter, the left observer was designated as data recorder and the right  
148 observer obtained digital photographs with a Canon 40D or Canon 70D camera and a 100– 400  
149 mm image-stabilized lens. The observers rotated between these two positions during each

150 survey. These images were used to confirm species identification (see below), refine estimates of  
151 group size and confirm sightings of calves. Each observer independently estimated the minimum  
152 and maximum number of animals in each sighting. A best estimate of group size was then  
153 established by integrating field observations and subsequent examination of digital images. Once  
154 photographs and sighting data were collected, the plane returned to the original cue position from  
155 which it had broken from the trackline and resumed survey effort.

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### 157 Species Identification

158 Beaked whale species identification was confirmed in the laboratory after review of  
159 digital photographs gathered during each sighting, using methods described in Read *et al.* (2014).  
160 Only photographs of extremely high quality that captured detailed physical features of an  
161 individual were utilized for species identification. Physical features diagnostic of *Ziphius*  
162 *cavirostris* are well-described and distinctive (Jefferson *et al.* 2008). *Mesoplodon* species, in  
163 contrast, are more difficult to discriminate. The placement of the mandibular teeth, which erupt  
164 only in adult males, can be used to identify species (Moore 1966, Mead 1989). Thus,  
165 mesoplodonts were only identified to species after an adult male, with visible erupted teeth, had  
166 been photographed. The physical characteristics of the adult male, and all other individuals  
167 within the same sighting, were used to identify past and current sightings to species, even if an  
168 adult male was not present in these sightings.

169 During the course of this study, *Mesoplodon europaeus* was consistently identified using  
170 this method. On 16 September 2015, a *M. mirus* adult male was also identified. This latter  
171 sighting occurred 25 km north of the study area, and is not included in any of the quantitative  
172 analyses presented herein, but photographic data from this sighting are presented here, given the



173 extremely rare occurrence and identification of this species at sea (Aguilar de Soto *et al.* 2017).  
174 Sightings of mesoplodonts that lacked sufficient detail to diagnose to species, due, for example,  
175 to environmental conditions or image quality, were termed “unidentified *Mesoplodon*”.

176 All sightings were plotted using *ArcGIS* Version 10.1 (ESRI). For temporal analysis,  
177 monthly sightings were plotted using Excel 2010 (Microsoft).

178

### 179 *Abundance and Density Estimates of Beaked Whales in the Cape Hatteras Survey Area*

180 The survey data were used to generate density estimates for all beaked whales combined,  
181 and for *Z. cavirostris* alone, using *Distance* sampling methods (Buckland *et al.* 2001) and then  
182 these estimates were adjusted to take into account the fact that not all individuals were available  
183 at the surface. The densities were then used to obtain abundance estimates over both the entire  
184 survey area and a subset of the area greater than 1,000 m depth as this was thought to be the  
185 preferred habitat of the taxa under consideration (Waring *et al.* 2001, Tyack *et al.* 2006).

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### 187 Estimation of detection probabilities

188 In conventional line transect sampling, the probability of detection depends only on the  
189 perpendicular distance of the sighting to the transect line ( $y$ ) and at zero perpendicular distance  
190 the probability of detection is assumed to be one (denoted by  $g(0)=1$ ). Both a hazard-rate ( $1-$   
191  $\exp(-y/\sigma)^{-b}$ ) and a half-normal ( $\exp(-y^2/2\sigma^2)$ ) form were considered as suitable forms for the  
192 detection functions ( $\sigma$  is the scale parameter). Thus, the probability of detection becomes a  
193 multivariate function,  $g(y, \mathbf{v})$ , representing the probability of detection at perpendicular distance  $y$   
194 and covariates  $\mathbf{v}$  ( $\mathbf{v} = v_1, \dots, v_Q$  where  $Q$  is the number of covariates). The scale term,  $\sigma$ , has the  
195 form:

196

$$197 \quad \sigma_k = \exp\left(\beta_0 + \sum_{q=1}^Q (\beta_q v_{kq})\right)$$

198

199 and  $\beta_0$  and  $\beta_q$  ( $q=1, \dots, Q$ ) are parameters to be estimated. With this formulation, it is assumed  
 200 that the covariates affect the rate at which detection probability decreases as a function of  
 201 distance, but not the shape of the detection function. The covariates considered for inclusion into  
 202 the detection function were Beaufort sea state, group size, cloud cover, visibility, glare (all  
 203 continuous), and species (factor). A forward, stepwise selection procedure was used to decide  
 204 which covariates to include in the model, with a minimum Akaike's Information Criterion (AIC)  
 205 inclusion criterion. All model selection was performed using a set of customized functions (mrds  
 206 v.2.1.14, Laake *et al.* 2014) in *R* (*R* Developmental Core Team, 2002). This facilitated estimation  
 207 of variance within *R* (see below).

208

### 209 Estimation of density surfaces

210 The 'count model' of Hedley *et al.* (2004) was implemented to model the trend in spatial  
 211 distribution of the different species. The response variable for this model is the estimated number  
 212 of individuals in a small segment  $i$  of trackline,  $\hat{N}_i$ , calculated using an estimator similar to the  
 213 Horvitz-Thompson estimator (Horvitz and Thompson 1952), as follows:

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$$215 \quad \hat{N}_i = \sum_{j=1}^{n_i} \frac{s_{ij}}{\int_0^w \hat{g}(y, v_{ij}) \pi(y) dy}, \quad i = 1, \dots, T,$$

216

217 where for segment  $i$ ,  $\int_0^w \hat{g}(y, v_{ij}) \pi(y) dy$  is the estimated probability of detection of the  $j$ th  
 218 detected group,  $n_i$  is the number of detected groups in the segment and  $s_{ij}$  is the size of the  $j$ th  
 219 group. The total number of effort segments is denoted by  $T$ . By assumption,  $\pi(y)$  the probability  
 220 density function of actual (not necessarily observed) perpendicular distances is uniform up to the  
 221 truncation distance; this is satisfied by locating transects randomly or with a random start point.

222 The above detection probability assumes detection on the trackline ( $g(0)$ ) is one, i.e. all  
 223 surface animals on the trackline are seen. However when estimated from a similar aerial survey  
 224 protocol to that used here, Forney *et al.* (1995) found  $g(0)$  corrected for perception bias was  
 225 actually 0.95 so this figure was used to modify the  $\hat{N}_i$ .

226 Note all animals must be at the surface to be seen, so to estimate the total population, a  
 227 further estimate of surface abundance needs to be estimated. To obtain an estimate of the total  
 228 population of beaked whales, the proportion of animals available at the surface has to be  
 229 considered. An index of availability at the surface for each sighting was made by considering the  
 230 reported proportion of time the animals spend at the surface. The probability of an individual  
 231 being available at the surface was given by

$$233 \quad P(Avail) = \frac{E[s]}{E[s]+E[d]} + E[d] \times \frac{(1-e^{-\frac{t}{E[d]}})}{E[s]+E[d]}$$

234  
 235 after Laake *et al.* (1997) where  $s$  = surface time,  $d$  = dive time and  $t$  = window of time during  
 236 which an animal is within the visual range of an observer. The time period that the animal was  
 237 within the visual range of the observer was taken to be the quotient of 973.4 m and the plane  
 238 speed. This distance was in turn based upon the mean perpendicular distance for sightings of

239 medium sized whales (i.e. beaked whales and pilot whales) of 421.5 m. This latter distance being  
240 the “height” of a right angle triangle (treating the hypotenuse as the base) horizontal from the  
241 plane encompassing the viewing angle of the observers (60° forward and 30° aft). Sensitivity to  
242 the assumed length of this “window of opportunity” was tested by considering a number of  
243 different window of opportunity lengths. A range from 833 m to 2 km, changed the estimated  
244 densities by only a few thousandths of an animal per kilometer<sup>2</sup>.

245         Given individual availability above, group availability (*Group avail*) was calculated as  
246 follows

$$247$$
$$248 \quad P(\textit{Group avail}) = 1 - (1 - P(\textit{Avail}))^k$$
$$249$$

250 where the right hand side represents the probability that at least one member of the group is at  
251 the surface during their diving behavior.  $k$  is a parameter which took different values dependent  
252 on what assumptions are made about the synchronicity of the individuals in the pod. If animals  
253 are perfectly synchronous the animals surface as one, so  $k = 1$ . If the animals surface  
254 independently of each other, then  $k$  is the corrected pod size. These two conditions, and one that  
255 assumed half the animals surfaced such that the effective number of independent surfacing  
256 “units” was half the estimated pod size, were used here. If pods come up in synchrony their  
257 availability at the surface is low leading to an increased estimate of abundance. Beaked whale  
258 dive and surface times were not available from Cape Hatteras, North Carolina, so comparable  
259 data were taken from *Mesoplodon densirostris* tagged in the Canaries (2003-2010) by the  
260 University of La Laguna and the Sea Mammal Research Unit, University of St. Andrews (see  
261 acknowledgements). Dive and surface times for *Ziphius* were taken from DeRuiter *et al.* (2013a),

262 available from DeRuiter *et al.* (2013b, see also Tyack *et al.* 2006 as the primary source of some  
263 of the data). Because the diving behaviors of mesoplodonts encountered at Cape Hatteras are not  
264 known, and because *Ziphius* dive behaviors in this region may be different from those in other  
265 geographic regions and habitats, we acknowledge that this approach provides only an estimate of  
266 group availability. These estimates will be improved in the future by using dive data for, and by  
267 understanding dive synchrony of, local ziphiids.

268       Having obtained the estimated number of individuals in each segment, the density in  
269 segment  $i$ ,  $\hat{D}_i$ , was estimated from  $\hat{N}_i / a_i$  where  $a_i$  is the area of segment  $i$ . Segment area was  
270 calculated as the length of the segment multiplied by twice the truncation distance, which was  
271 decided when modelling the detection function (see results). The realized effort was divided into  
272 distinct segments based on when the plane had gone on or off search effort and whether there  
273 was a change in environmental characteristics (not currently of relevance to beaked whales but of  
274 relevance to other species encountered during these surveys). A target segment length of 10 km  
275 was chosen as an appropriate compromise between maximizing the ratio of nonzero to zero  
276 segments, maintaining environmental resolution and giving some measure of spatial  
277 independence, although some segments were much smaller if there had been a break in effort or  
278 change in environmental conditions. Due to the different segment areas, segment area was  
279 included as a weight (a term with a known regression coefficient) in the subsequent model.  
280 Analyzing the data in this way allowed subsets of the survey area to be readily created based on  
281 environmental covariates.

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### 285 Prediction

286           The selected models were used to predict density of beaked whales using a uniform 2-  
287 minute resolution prediction grid. Abundance was estimated by numerically integrating under  
288 this predicted density surface. As a uniform density is assumed this is equivalent to a design  
289 based estimate of density. The estimation was implemented this way because of the requirement  
290 to estimate other species' abundances from the survey. Two areas were considered, the first  
291 including the entire surface area and a more restricted subarea where depth was greater than  
292 1,000 m (see above).

293

### 294 Estimation of uncertainty

295           Variance was estimated by repeating (1,000 times) the entire abundance estimation  
296 process on samples drawn from the data to obtain a distribution of abundance estimates, i.e. a  
297 nonparametric bootstrap. Samples of dive times and surface times were also redrawn for the  
298 availability estimate. Samples were obtained by sampling transects (and associated sightings), at  
299 random and with replacement, such that the selected effort reflected the effort in the original  
300 sample. Confidence intervals were obtained from this resampling-derived distribution using the  
301 2.5% and 97.5% percentiles to obtain the lower and upper limits of the 95% confidence interval.

302

### 303 *Strandings*

304           Beaked whale strandings are relatively rare events in North Carolina (Byrd *et al.* 2014).  
305 To increase the sample size for comparison to sightings during the current study, all beaked  
306 whale strandings from January 1993 through December 2015 ( $n= 47$ ) were included. Most of  
307 these strandings were thoroughly investigated with voucher skeletal material collected to confirm

308 species identification and many were accessioned into the U.S. National Museum of Natural  
309 History or the North Carolina Natural Science Museum. The data utilized here included species  
310 identification (when known), date, and location of each beaked whale stranding. All strandings  
311 were plotted using *ArcGIS* Version 10.1 (ESRI). For temporal analysis, monthly strandings were  
312 plotted using Excel 2010 (Microsoft).

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## 315 RESULTS

316

### 317 *Species Identification*

318 Two species of beaked whales were photographically confirmed during surveys: *Ziphius*  
319 *cavirostris* and *Mesoplodon europaeus*. We also describe a *M. mirus* photographed outside the  
320 Cape Hatteras survey area.

321 *Z. cavirostris* displayed distinctive features characteristic of the species (Fig. 2),  
322 including a relatively robust body shape, a short beak, and a head that tended to be lighter in  
323 color than the body. Body coloration varied among individuals, ranging from pale to dark gray,  
324 and rusty to caramel brown. The dorsal fin was typically falcate, and larger individuals displayed  
325 heavier, linear scarring over the dorsal thorax.

326 The presence of *M. europaeus* was confirmed from a sighting of an adult male on 18 July  
327 2013 (Fig. 3). This individual displayed erupted mandibular teeth at a position less than halfway  
328 along the rostrum's length from the tip. This tooth placement confirmed its identity as *M.*  
329 *europaeus* (Moore 1966, Mead 1989 and Smithsonian Institution's Beaked Whale Identification  
330 Guide [http://vertebrates.si.edu/mammals/beaked\\_whales/pages/main\\_menu.htm](http://vertebrates.si.edu/mammals/beaked_whales/pages/main_menu.htm)). The coloration  
331 patterns of other individuals in this sighting were used as diagnostic features to identify this

332 species in other sightings (assuming that this was a monospecific group), including three  
333 sightings made on 9 June 2012, 28 May 2013, and 16 July 2013, before this adult male was  
334 identified (Fig. 4). An additional sighting of a single adult male with erupted teeth was recorded  
335 on 14 May 2014 (Fig. 4). Dorsolateral color patterns were used to identify a pair of beaked  
336 whales (not associated with an adult male) observed on 11 June 2014 as *M. europaeus*.

337         The coloration patterns of the larger *M. europaeus* individuals associated with the adult  
338 male photographed on 18 July 2013 were distinctive (Fig. 4). Each individual displayed a  
339 relatively broad, dark gray stripe along its mid-dorsal surface. The stripe began behind the  
340 blowhole and extended to the dorsal fin. Multiple, thin dark gray stripes projected laterally from  
341 the broad dorsal stripe; these thin, transverse, “tiger stripes” terminated above the mid-lateral  
342 line. These pigmentation patterns are consistent with lateral photographs of *M. europaeus*, taken  
343 from vessels, presented in Jefferson *et al.* (2008) and the illustration presented in Aguilar de Soto  
344 *et al.* (2017). Interestingly, the two adult male *M. europaeus* did not share the distinctive dorsal  
345 pigmentation pattern. The male photographed on 18 July 2013 displayed a relatively uniform  
346 gray dorsum, bearing a number of lightly pigmented linear scars (Fig. 3). The dorsal surface of  
347 the male photographed on 14 May 2014 was irregularly pigmented, with a large pale-scarred  
348 area extending across the cranial third of the dorsum (Fig. 4). These scarred areas are believed to  
349 result from agonistic interactions among males that occurs in many beaked whale species (Mead  
350 1989). In all individuals of this species, a subcircular, lightly pigmented patch was present dorsal  
351 and rostral to the eye, which appeared darkly pigmented.

352         On 16 September 2015, an adult male *M. mirus* (Fig. 5), with erupted teeth, was  
353 photographed with another closely associated individual. In this species the teeth erupt at the  
354 distal-most tip of the mandibles, similar to those in *Z. cavirostris*, but the overall coloration and



355 body proportions of the whale confirmed that it was a mesoplodont. The body shape of the male  
356 *M. mirus* was more laterally compressed, and the rostrum more elongated than those of *M.*  
357 *europaeus*. Caudal to the blowhole, the dorsal midline appeared to be relatively sharp, almost  
358 keel-like, and was lighter gray in coloration relative to the dorsal flank. A few lightly pigmented  
359 linear scars were present across the dorsum. The area surrounding the blowhole was more lightly  
360 pigmented relative to other dorsal body surfaces, consistent with the description of the lateral  
361 head by Aguilar de Soto *et al.* (2017), based upon photographs taken during vessel surveys.  
362 Otherwise the body was relatively uniformly gray in color in both individuals photographed (as  
363 is also illustrated by Aguilar de Soto *et al.* 2017), suggesting that identification of females and  
364 young of this species could remain challenging at sea.

365

#### 366 *Sightings during aerial surveys*

367 *Z. cavirostris* was the most commonly sighted species of beaked whale, representing 60%  
368 of all sightings (Fig. 1, Table 2). *M. europaeus* contributed 8% and unidentified mesoplodonts  
369 made up the remaining 32% of beaked whale sightings. *Z. cavirostris* were sighted in every  
370 month of the year, while *M. europaeus* was observed only in May, June and July (Fig. 6a).  
371 Unidentified mesoplodonts were observed in all months of the year except September and  
372 October.

373 Most beaked whale sightings (64 of 74) occurred at or beyond the 1,000 m isobath (Fig.  
374 1). Most sightings (37 of 44) of *Z. cavirostris* occurred at or north of Cape Hatteras Point, while  
375 *M. europaeus* and unidentified mesoplodonts were distributed more evenly across the study area.

376 The tendency for beaked whale sightings to occur at or beyond the 1,000 m isobath was  
377 also observed in Onslow Bay (Fig. 8). All sightings at this site were of unidentified

378 mesoplodonts, suggesting that the pattern of species distribution observed in the Cape Hatteras  
379 survey area may continue southward. This result should be viewed with caution, however, as it is  
380 based upon only three days of surveys that extended beyond the Onslow Bay core study area.

381

### 382 *Beaked Whale Abundance and Density Estimates in the Cape Hatteras Study Area*

383 To produce a robust detection function with a low uncertainty, sightings of all medium  
384 sized whales (ziphiids, pilot whales, kogiids, and *Pseudorca*) were considered. A total of 175  
385 groups were considered within a truncation distance of 900 m, 62 of which were of ziphiids (23  
386 of *Mesoplodon* spp., 1 *M. mirus*, 5 *M. europaeus*, and 33 *Ziphius cavirostris*). The final selected  
387 model consisted of distance only (Fig. 7), which gave a mean probability of detection of 0.652  
388 (SE: 0.091) with truncation distance of 900 m.

389 The surface density of all beaked whales, uncorrected for availability bias, was estimated  
390 as 0.005 (95% CI 0.003-0.008) whales/km<sup>2</sup> over the entire Cape Hatteras survey area, leading to  
391 an abundance estimate of 80 (50-130) animals in total (Table 3). When the subarea deeper than  
392 1,000 m is considered, the mean density is 0.007 (95% CI 0.005-0.011) whales/km<sup>2</sup>, for a total of  
393 abundance of 60 (40-100) whales. Density estimates that corrected for animal availability at the  
394 surface, yielded values that were 2.4 to 5.6 times higher than estimates for surface only animals,  
395 depending upon the assumptions of surfacing synchronicity (Table 3). Density and abundance  
396 estimates for *Z. cavirostris*, the most commonly sighted beaked whale species, are also presented  
397 in Table 3.

398

399

400

401 *Beaked whale strandings in North Carolina*

402           Between January 1993 and December 2015, forty-seven beaked whale strandings were  
403 recovered in North Carolina (Fig. 8 and Table 4). The latitudinal pattern and species composition  
404 of strandings differed from that of sightings. *Z. cavirostris* contributed only 9% of all beaked  
405 whale strandings, and these events occurred at or south of the southern-most sightings of this  
406 species. No *Z. cavirostris* stranded in North Carolina from June 2000 to December 2015. *M.*  
407 *europaeus* comprised 57% of all beaked whale strandings, and their distribution stretched both  
408 north and south of the range of confirmed sightings of this species. Half of all *M. densirostris*  
409 and all *M. mirus* strandings have occurred along a small portion of the northern Outer Banks of  
410 North Carolina. One species in the stranding record, *M. densirostris*, has not been detected  
411 during aerial surveys off the North Carolina coast.

412           Beaked whales have stranded in all months of the year in North Carolina (Fig. 6b). For all  
413 beaked whale species combined, strandings did not vary significantly by month (chi-squared =  
414 16.6, df = 11,  $P = 0.12$ ), but did by marine season (i.e. January through March = winter, *etc.*; chi-  
415 squared = 8.2, df = 3,  $P = 0.041$ ), with disproportionately more strandings in spring.

416

417 DISCUSSION

418           Beaked whales are present year-round off Cape Hatteras, North Carolina, USA. *Ziphius*  
419 *cavirostris* was encountered in every month of the year, and mesoplodont whales were  
420 encountered in 10 out of 12 mo. Of the six species of beaked whales known to occur in the  
421 Northwest Atlantic, four - *Z. cavirostris*, *Mesoplodon densirostris*, *M. mirus*, and *M. europaeus* -  
422 occur off Cape Hatteras (MacLeod 2000, MacLeod *et al.* 2006). Two of these species were  
423 photographically documented within the survey area and a third was encountered just a few

424 kilometers to the north (Fig. 2-5). To our knowledge, this is the first aerial survey to successfully  
425 discriminate mesoplodonts to species, a task that can be difficult even with a stranded specimen  
426 in hand. The ability to identify these species was entirely dependent upon clear photographic  
427 records of adult males with erupted mandibular teeth. The consistent sightings of *M. europaeus*  
428 in the study area also permitted description of species-specific pigmentation patterns that allowed  
429 confirmation of females and juveniles of this species. The opportunity to obtain such  
430 photographs is rare, but these results demonstrate that it is possible to identify mesoplodonts to  
431 species during aerial surveys.

432 The overall density of all beaked whales at the Cape Hatteras study site was remarkable  
433 (Table 3), with surface density estimates of 0.005/km<sup>2</sup> for the entire survey area, and 0.007/ km<sup>2</sup>  
434 for the deep subarea. These values, which are not corrected for availability bias, are higher than  
435 most g(0) corrected values, excluding those for *Berardius bairdii*, presented by Barlow *et al.*  
436 (2006) in their comprehensive review of beaked whale densities from around the globe (see their  
437 Table 2). The perception and availability corrected density values of 0.019-0.042/km<sup>2</sup> in the deep  
438 subarea (Table 3) are higher than for any beaked whale species, except *Berardius*, reported by  
439 Barlow *et al.* (2006).

440 Cape Hatteras, at the convergence of the Labrador Current and Gulf Stream, is a region  
441 of high biological productivity (Schaff *et al.* 1992). The continental slope and deep shelf waters  
442 at this site experience extremely high rates of carbon flux and sedimentation (reviewed in  
443 Cahoon *et al.* 1994), host dense assemblages of benthic macrofauna (Schaff *et al.* 1992, Blake  
444 and Hilbig 1994), and represent a transition and transport zone for larval fishes from the Mid-  
445 Atlantic and South Atlantic Bights (Grothues and Cowan 1999, and Grothues *et al.* 2002). The

446 results of this study demonstrate that these waters also host extremely high densities of multiple  
447 species of beaked whales.

448 Barlow *et al.* (2006) identified both sea state and observer experience as critical factors in  
449 the ability to detect smaller beaked whales. In the present study, surveys were conducted in good  
450 sighting conditions by two highly-trained observers, each with multiple years of experience.  
451 Barlow *et al.* (2006) also noted that many previous beaked whale abundance estimates included  
452 shallow shelf and slope waters, where beaked whales were unlikely to occur. Beaked whale  
453 density estimates should be generated from slope or deep waters – i.e. known beaked whale  
454 habitat. The present study accomplished this goal, and as would be predicted, estimates of  
455 beaked whale densities are comparatively very high. The present surveys also occurred year-  
456 round and across multiple years. Multi-year and/or multi-season focused survey efforts to assess  
457 the presence of beaked whales are rare (Balcomb and Claridge 2001, MacLeod and Zuur 2005,  
458 Soto 2006, Claridge 2013, Arcangeli *et al.* 2014, Cañadas and Vazquez 2014), and there are few  
459 other comparable data sets generated from focused, multi-year, year-round survey efforts.

460 Pyenson (2011) compared stranding and sighting records at eight locations across the  
461 globe and discovered that stranding records provided “high fidelity” records of the species  
462 richness and relative abundance of living cetacean assemblages documented through surveys.  
463 He also determined that species richness was almost always higher in the stranding record than  
464 in the survey record. In some regards, the results presented here support these conclusions.  
465 Beaked whales stranded in all months of the year in North Carolina, reflecting the results of the  
466 aerial surveys described here. More beaked whale species were recovered as stranded specimens  
467 in North Carolina than observed during aerial surveys, with one species, *Mesoplodon*  
468 *densirostris*, found only in the stranding record.

469           The relative abundance of species differed dramatically across the stranded and sighted  
470 data sets. The most commonly sighted species, *Z. cavirostris* (60% of all beaked whale sightings)  
471 was rare in the stranded sample (8% of all stranding). Likewise, *M. europaeus* comprised only  
472 8% of all sightings (although this species is also likely to be included in the *Mesoplodon* spp.  
473 sightings), but was the most common stranded beaked whale species in North Carolina (57% of  
474 all strandings). *Z. cavirostris* and *M. europaeus* both occur off Cape Hatteras, but during the  
475 study period no *Z. cavirostris* stranded in this region. The reasons for the differences in the  
476 stranding and sighting records are currently unknown, are likely to be complex, but may be  
477 important to inform mitigation strategies under MMPA authorizations issued by the National  
478 Oceanographic and Atmospheric Administration (NOAA) for U.S. Navy Atlantic Fleet Training  
479 and Testing (AFTT) activities, as well as for seismic exploration. Under the Stranding Response  
480 Plan in the current MMPA authorization for AFTT  
481 ([www.nmfs.noaa.gov/pr/pdfs/permits/aftt\\_stranding\\_response.pdf](http://www.nmfs.noaa.gov/pr/pdfs/permits/aftt_stranding_response.pdf)), if an “uncommon stranding  
482 event”, which includes the stranding of a single beaked whale, occurs locally during a major  
483 training exercise, the Navy may be required to alter their activities. The lack of *Z. cavirostris*  
484 strandings in the Cape Hatteras region suggests that this mitigation strategy may not be as  
485 effective for this species at this site since they appear to be less likely to strand regardless of the  
486 cause.

487           Effective management and conservation of cetaceans requires knowledge of their  
488 abundance and distribution in areas where they are vulnerable to anthropogenic activities  
489 (Hammond *et al.* 2013). The waters off Cape Hatteras are an important year-round habitat for  
490 several beaked whale species. These results complement those of Roberts *et al.* (2016), who  
491 identified this area as a hotspot of cetacean biodiversity, and one with high beaked whale

492 abundance. This site is also currently utilized by the U.S. Navy for its training and testing  
493 activities and has been included in the areas of interest for large-scale commercial seismic  
494 surveys. Beaked whale species appear to be particularly vulnerable to certain types of  
495 anthropogenic disturbance (Barlow *et al.* 2006, Cox *et al.* 2006, Tyack *et al.* 2011). Therefore,  
496 building on the recommendations of Cox *et al.* (2006) and Barlow *et al.* (2006), future research  
497 efforts in this area should be aimed at enhancing our understanding of beaked whale: (a)  
498 population structure through photo-ID, genetic sampling and telemetry; (b) diving behavior and  
499 ecology, using archival tags and satellite-linked dive recorders; (c) anatomy and physiology,  
500 through the detailed investigation of strandings; and (d) behavioral responses to anthropogenic  
501 sounds, through controlled exposure experiments. Such studies are required to fully understand  
502 and mitigate anthropogenic impacts on multiple species in this important beaked whale habitat.

503

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Month	Effort (km) 2011	Effort (km) 2012	Effort (km) 2013	Effort (km) 2014	Effort (km) 2015	Total Effort (km) 2011 - 2015	Total Sightings
January	0	1325	0	0	0	1325	3
February	0	582	0	583	0	1165	2
March	0	1456	149	0	0	1605	2
April	0	0	0	1010	0	1010	2
May	766	1160	709	407	492	3534	19
June	964	1901	0	1068	549	4482	9
July	1031	0	1755	1192	142	4120	9
August	0	701	1744	1164	648	4257	12
September	0	735	0	0	635	1370	3
October	1184	0	556	990	0	2730	2
November	1030	314	0	0	551	1895	6
December	0	981	0	573	0	1554	5
<b>Totals</b>	<b>4975</b>	<b>9155</b>	<b>4913</b>	<b>6987</b>	<b>3017</b>	<b>29047</b>	<b>74</b>

**Table 1.** Monthly aerial survey effort, and beaked whale sightings, at the Cape Hatteras, North Carolina survey site during the study period, May 2001 through December 2015.

235x88mm (300 x 300 DPI)

Peer Review

Species	# of Sightings	# of Individuals	Mean Group Size	Range Group Size
<i>Z. cavirostris</i>	44	128	2.9	1 to 8
<i>M. europaeus</i>	6	16	2.6	1 to 5
<i>Mesoplodon</i> spp.	24	61	2.5	1 to 6

**Table 2.** Beaked whale sightings, by species, at the Cape Hatteras, North Carolina survey site during the study period.

189x21mm (300 x 300 DPI)

For Peer Review

All Beaked Whales	Whole Site		1000m+ Depth	
	Estimated density animals/km <sup>2</sup>	Estimated numbers animals/km <sup>2</sup>	Estimated density animals/km <sup>2</sup>	Estimated numbers animals/km <sup>2</sup>
Surface only	0.005 (0.003 – 0.008)	80 (50 - 130)	0.007 (0.005 – 0.011)	60 (40 - 100)
Whales surface individually	0.012 (0.008 – 0.019)	190 (130 - 300)	0.019 (0.012 – 0.030)	170 (110 - 260)
Whales surface such that half the pod comes up individually	0.022 (0.015 – 0.033)	350 (240 - 520)	0.034 (0.022 – 0.054)	300 (190 - 480)
Whales surface as one group	0.028 (0.018 – 0.045)	420 (280 - 710)	0.042 (0.026 – 0.066)	370 (230 - 580)
<i>Ziphius cavirostris</i>				
Surface only	0.003 (0.002 – 0.005)	50 (30 - 80)	0.004 (0.002 – 0.007)	40 (20 - 60)
Whales surface individually	0.006 (0.003 – 0.011)	90 (50 - 170)	0.008 (0.004 – 0.015)	70 (40 - 130)
Whales surface such that half the pod comes up individually	0.009 (0.005 – 0.018)	140 (80 - 280)	0.013 (0.008 – 0.026)	110 (70 - 230)
Whales surface as one group	0.012 (0.007 – 0.024)	190 (110 - 380)	0.017 (0.008 – 0.034)	150 (70 - 300)

**Table 3.** Density estimates (+/- 95% CI) for all beaked whales (top panel) and for *Ziphius cavirostris* only (bottom panel) at the Cape Hatteras, North Carolina survey site during the study period, for both the entire survey area and the sub-area consisting of locations with depth greater than 1000m. Note that differences in density estimates, corrected for availability bias, vary dependent upon surfacing synchronicity.

221x92mm (300 x 300 DPI)

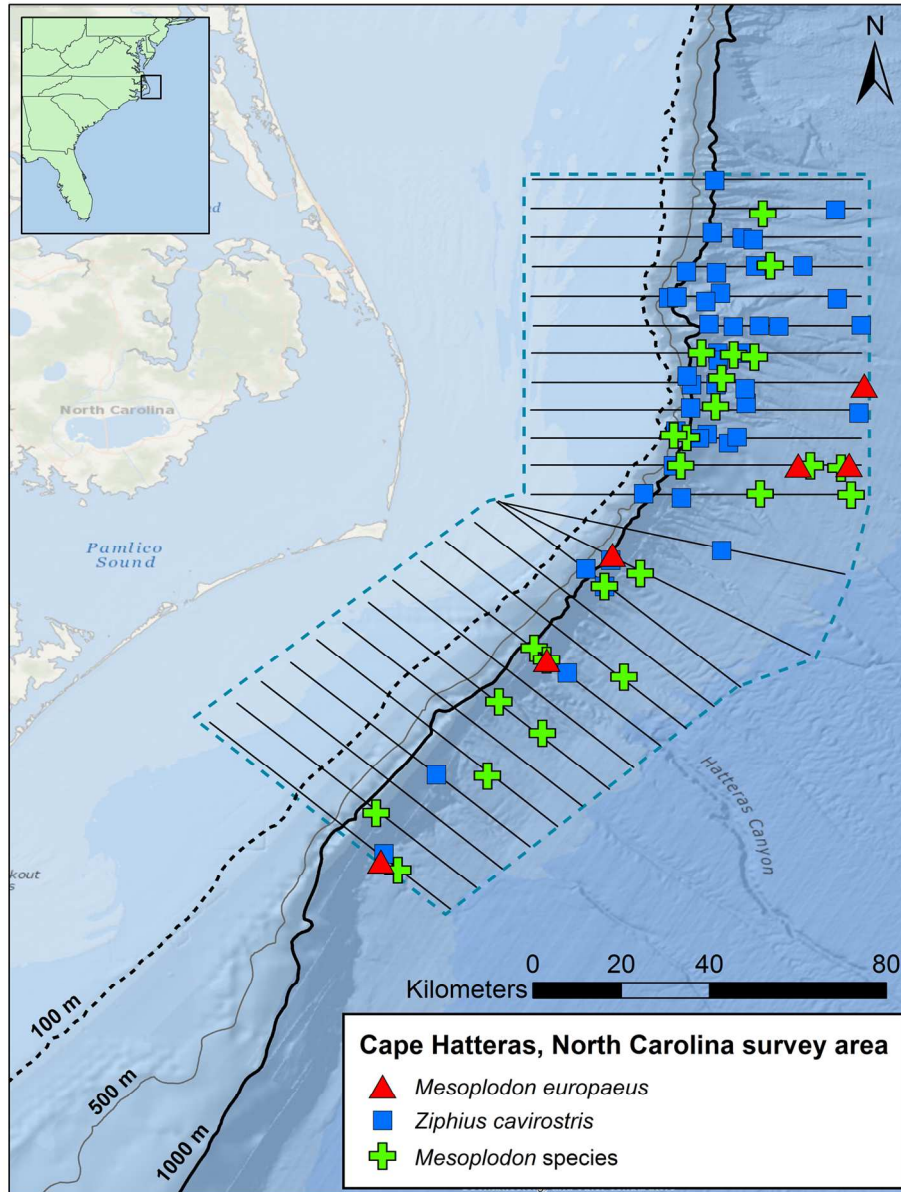
<b>Species</b>	<b># of Strandings</b>	<b>Inclusive dates</b>	<b># of Males</b>	<b># of Females</b>
<i>Z. cavirostris</i>	4	May 1996 - Jun 2000	0	4
<i>M. europaeus</i>	27	Jul 1993 - Jan 2015	11	16
<i>M. densirostris</i>	8	Sep 2001 - June 2012	3	5
<i>M. mirus</i>	3	Oct 2003 - Sep 2012	1	2
<i>Mesoplodon</i> spp.	5	Jun 1993 - May 2015	1	3

**Table 4.** Beaked whale strandings, by species, recovered in North Carolina from January 1993 through December 2015.

174x32mm (300 x 300 DPI)

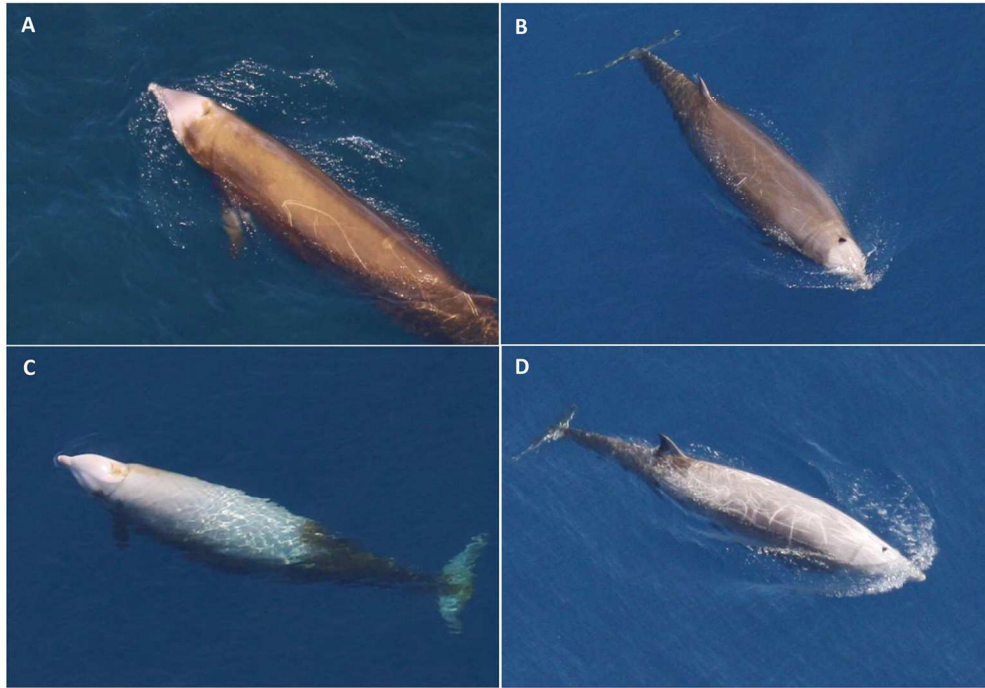
For Peer Review





**Figure 1.** Cape Hatteras, North Carolina survey site, tracklines flown and on-effort beaked whale sightings during the study period. Note beaked whales were encountered almost exclusively in waters 1000m or deeper.

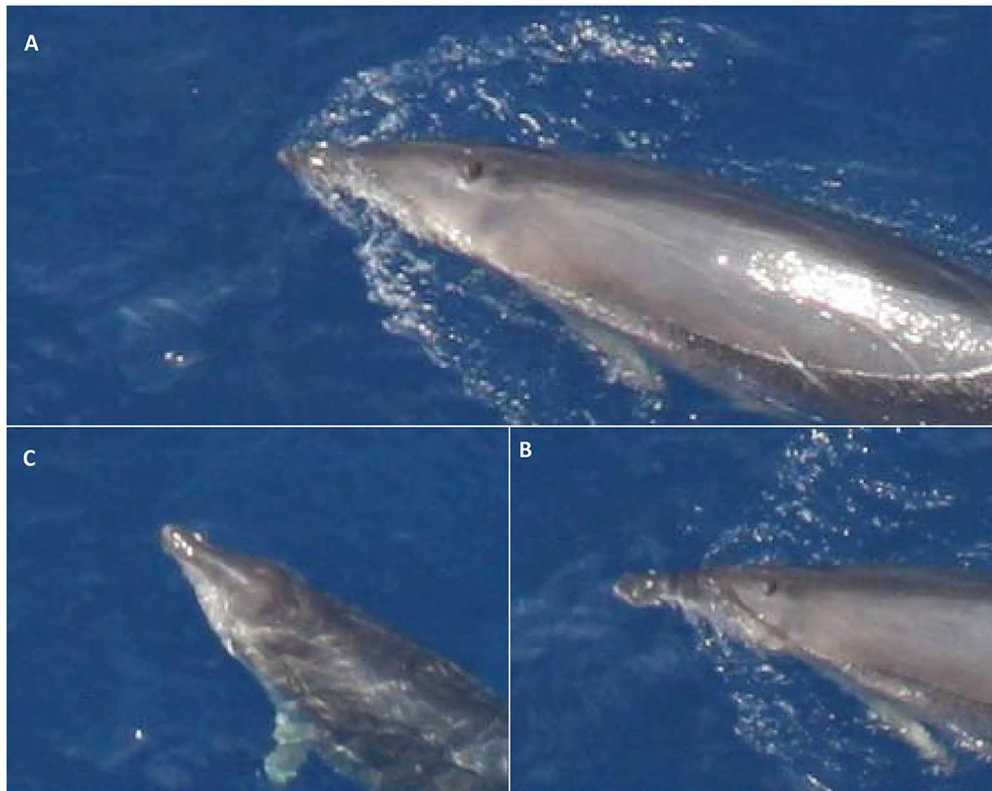
134x177mm (300 x 300 DPI)



**Figure 2.** Four *Ziphius cavirostris* individuals encountered in the Cape Hatteras, North Carolina survey site during the study period. A-D display gradation of scarring patterns observed in this species at the survey site.

139x97mm (300 x 300 DPI)

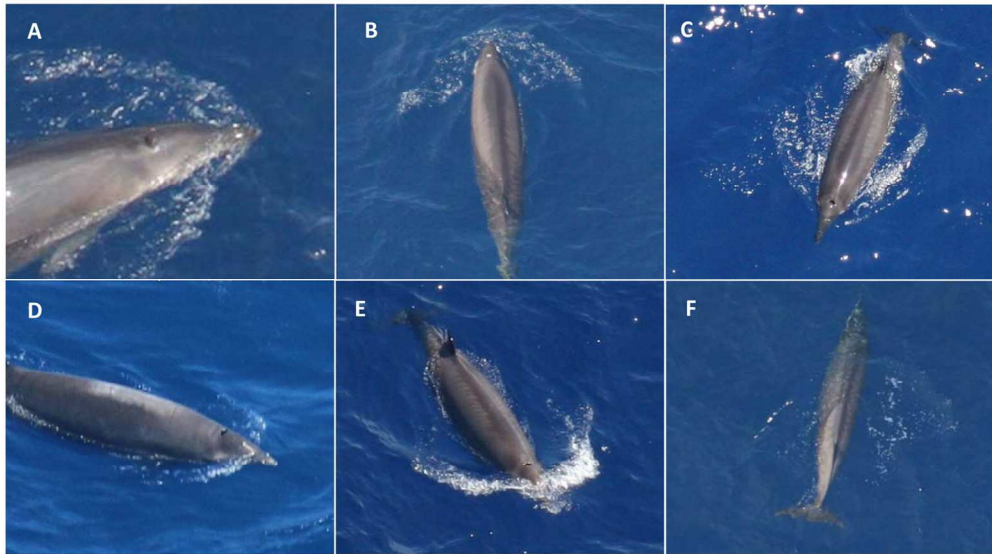
view



**Figure 3.** A series of photographs of an adult male *Mesoplodon europaeus* during a single surfacing event on 18 July 2013 in the Cape Hatteras, North Carolina survey site, where A is at the surface and the best image, B is just surfacing and C is just diving. All display the erupted mandibular teeth at a position less than halfway along the rostrum's length from the tip, which confirms species identification.

132x105mm (300 x 300 DPI)





**Figure 4.** Six *Mesoplodon europaeus* individuals encountered in the Cape Hatteras, North Carolina survey site during the study period. A. Adult male photographed on 18 July 2013 (see Figure 3). B. Individual associated with adult male (A) during the 18 July 2013 sighting. C. Individual sighted on 28 May 2013. D. Adult male (note tooth position) sighted on 14 May 2014. E. Individual sighted on 16 July 2013. F. Individual sighted on 11 July 2014.

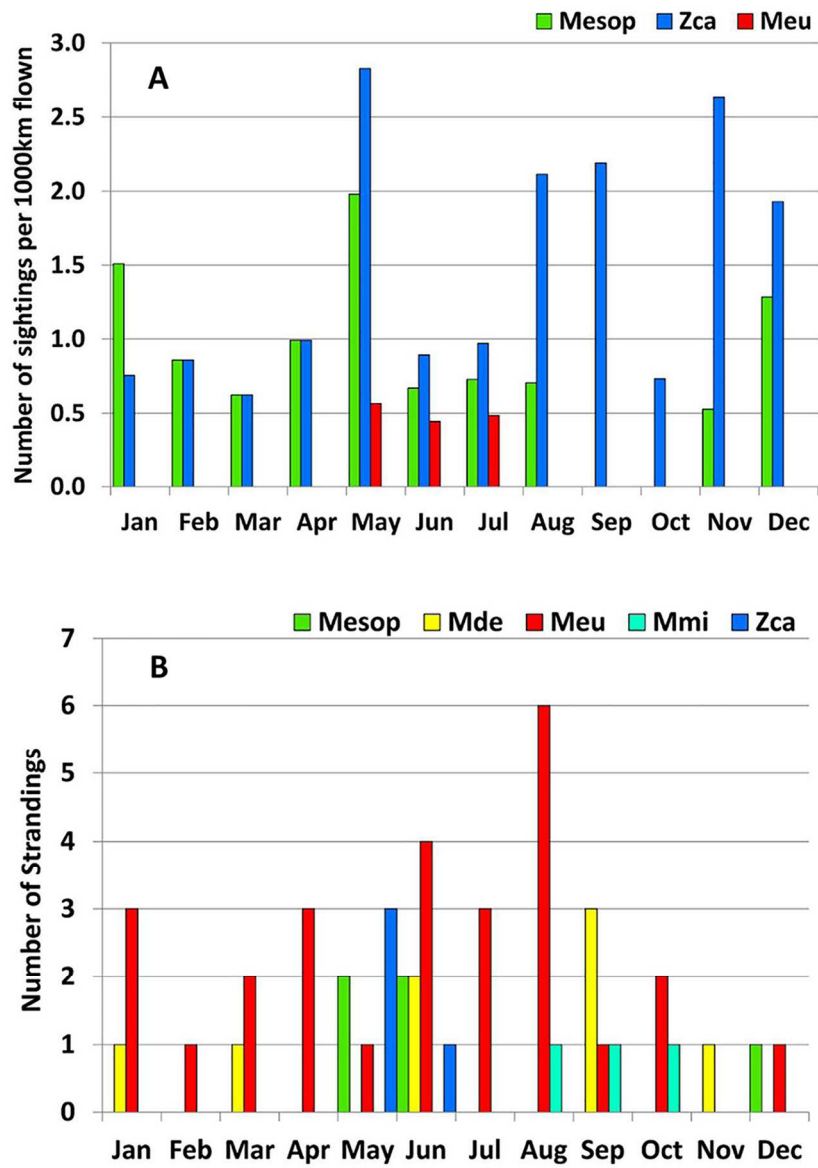
147x82mm (300 x 300 DPI)



**Figure 5.** An adult male *Mesoplodon mirus* encountered with another individual on 16 September 2015, at a position 25 km north of the Cape Hatteras, North Carolina survey site during the study period. Tooth placement at the tip on the mandibles confirms species identification.

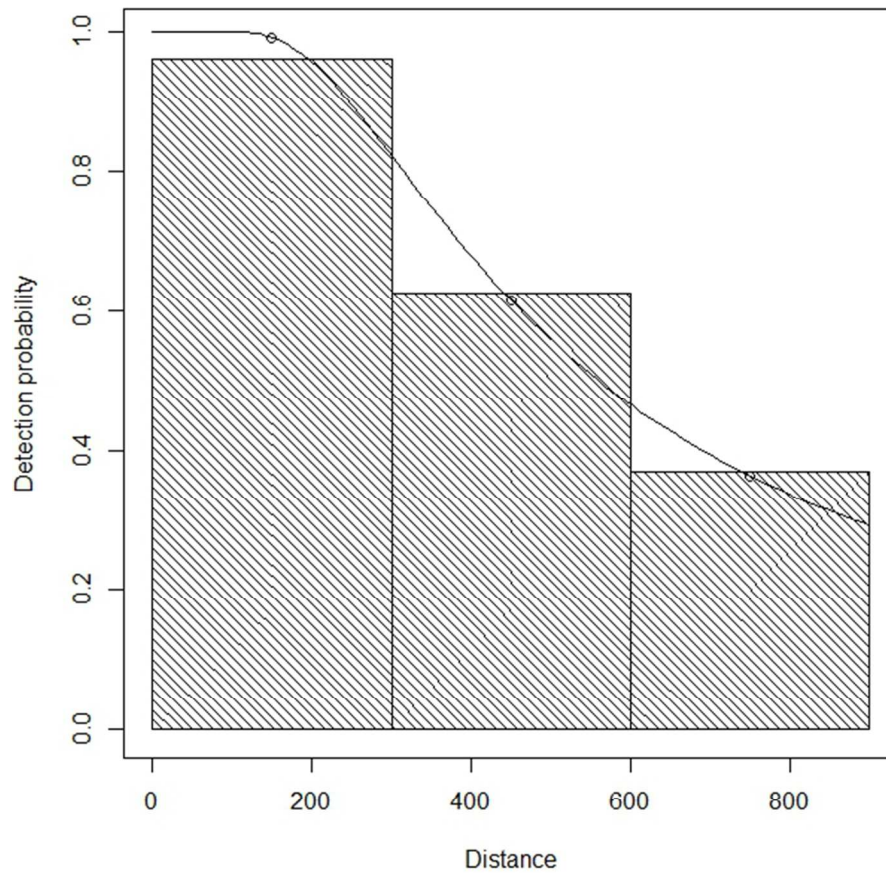
132x93mm (300 x 300 DPI)

view



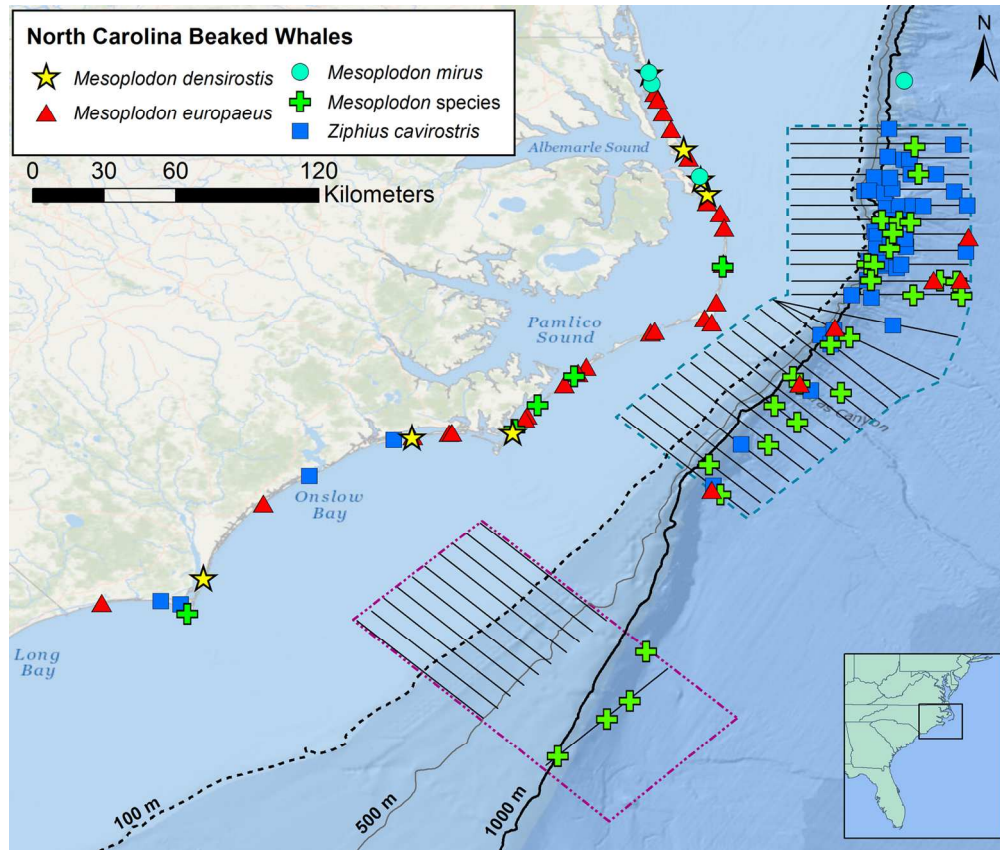
**Figure 6.** Beaked whale sightings and strandings. A. Cumulative monthly on-effort sightings of beaked whales, per 1,000 km of trackline flown, in the Cape Hatteras, North Carolina survey site during the study period (May 2011 through November 2015). B. Cumulative monthly strandings of beaked whales in North Carolina from January 1993 through December 2015.

116x156mm (300 x 300 DPI)



**Figure 7.** Probability of detection with distance (different levels shown by circles) for beaked whales (assuming detection on the trackline = 0.95). Solid line: mean fit against distance. NOTE: There is a strip width that cannot be observed directly under that plane. Thus, the actual left truncation distance is 149 m.

237x236mm (72 x 72 DPI)



**Figure 8.** Geographic positions of beaked whale sightings and strandings. Sightings include those during the study period at the Cape Hatteras, North Carolina survey site and those off the shelf break in Onslow Bay from June 2007 to June 2010. Strandings data include all beaked whales that have been documented in North Carolina from January 1993 through December 2015.

152x128mm (300 x 300 DPI)