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Joy E. Stanistreet; Douglas P. Nowacek; Andrew J. Read; Simone Baumann-Pickering; Hilary B. Moors-Murphy; Sofie M. Van Parijs

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Effects of duty-cycled passive acoustic recordings on detecting the presence of beaked whales in the northwest Atlantic

Joy E. Stanistreet,[a] **Douglas P. Nowacek, and Andrew J. Read**
Duke University Marine Laboratory, 135 Duke Marine Lab Road, Beaufort,
North Carolina 28516, USA
joy.stanistreet@duke.edu, doug.nowacek@duke.edu, aread@duke.edu

Simone Baumann-Pickering
Scripps Institution of Oceanography, University of California San Diego,
9500 Gilman Drive, La Jolla, California 92093, USA
sbaumann@ucsd.edu

Hilary B. Moors-Murphy
Bedford Institute of Oceanography, 1 Challenger Drive, Dartmouth, Nova Scotia B2Y 4A2,
Canada
hilary.moors-murphy@dfo-mpo.gc.ca

Sofie M. Van Parijs
Northeast Fisheries Science Center, 166 Water Street, Woods Hole, Massachusetts 02543,
USA
sofie.vanparijs@noaa.gov

Abstract: This study investigated the effects of using duty-cycled passive acoustic recordings to monitor the daily presence of beaked whale species at three locations in the northwest Atlantic. Continuous acoustic records were subsampled to simulate duty cycles of 50%, 25%, and 10% and cycle period durations from 10 to 60 min. Short, frequent listening periods were most effective for assessing the daily presence of beaked whales. Furthermore, subsampling at low duty cycles led to consistently greater underestimation of *Mesoplodon* species than either Cuvier's beaked whales or northern bottlenose whales, leading to a potential bias in estimation of relative species occurrence.

[CFM]
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1. Introduction

Passive acoustic monitoring (PAM) with autonomous recording instruments is a common technique used to study patterns of cetacean occurrence. Over the past several decades, this method has been applied most extensively to record low-frequency vocalizations from baleen whales, and is particularly valuable for monitoring remote locations and detecting rare or elusive species infrequently encountered at sea (e.g., Mellinger *et al.*, 2007; Sousa-Lima *et al.*, 2013). Recent technological improvements in the performance of autonomous recorders have led to the increasing use of PAM to detect higher frequency signals, including odontocete echolocation (Sousa-Lima *et al.*, 2013). This approach has particular value for studying beaked whales (family Ziphiidae), which are among the most difficult cetacean species to observe due to their offshore distributions and deep-diving behavior. Detection of beaked whale echolocation signals using autonomous, seafloor-mounted recorders offers unique insight into the occurrence and foraging activity of these species, especially over long time scales and in poorly-surveyed regions (e.g., Baumann-Pickering *et al.*, 2014).

Most beaked whale species produce frequency-modulated upswept pulse signals with center frequencies ranging from approximately 20 kHz to nearly 70 kHz (Baumann-Pickering *et al.*, 2013). Detection of these signals in passive acoustic recordings requires the use of high sampling rates (>100 kHz), which quickly leads to the accumulation of many terabytes of acoustic data over weeks or months of monitoring. Despite rapid advances in recording technology, data storage capacity remains the primary limiting factor in deployment durations of autonomous recording instruments,

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[a] Author to whom correspondence should be addressed.

particularly at such high sampling rates (Sousa-Lima *et al.*, 2013). Recorder deployment and recovery is both costly and logistically challenging, so the collection of high-frequency data for prolonged periods often involves a reduced recording schedule, employing a duty cycle to extend the duration of each deployment (e.g., Au *et al.*, 2013). Using this approach, recordings are made for a specified time period at a regularly repeating interval, alternating with a non-recording period to reduce the amount of data collected per day and extend the overall monitoring period.

Recording schedules are often chosen based primarily on practical considerations, such as the specifications of the recording instrument, the required sampling rate, and the desired deployment duration, rather than detailed prior knowledge of the target species' acoustic behavior and detectability. However, it is important to consider any biases that may be introduced by using a reduced recording schedule (Thomisch *et al.*, 2015). If the duty cycle listening period and recording interval are not appropriately matched to the duration and timing of acoustic events of interest, potential detections may be missed and species occurrence underestimated (Miksis-Olds *et al.*, 2010; Sousa-Lima *et al.*, 2013; Thomisch *et al.*, 2015).

These considerations are rarely addressed in PAM studies, and may be especially important when using PAM to establish baseline information on the spatial and temporal occurrence of beaked whales, because underlying patterns in the relative occurrence and acoustic behavior of these species in most regions are poorly known. In this paper we examine the potential effects of duty cycles on the assessment of daily presence of beaked whale echolocation signals in passive acoustic recordings, using datasets from three locations in the northwest Atlantic as case studies.

2. Methods

2.1 Data collection

Continuous passive acoustic recordings were collected at three locations along the continental shelf slope in the northwest Atlantic. In the mid-Atlantic region off the U.S. east coast, recordings were made offshore of Cape Hatteras, North Carolina (35° 20′ N, 74° 51′ W) from May 30, 2013 to March 14, 2014 (289 days) and near Norfolk Canyon, Virginia (37° 10′ N, 74° 28′ W) from June 20, 2014 to April 4, 2015 (289 days). At both sites, a High-frequency Acoustic Recording Package (HARP; Wiggins and Hildebrand, 2007) was deployed at a depth of approximately 975 m, programmed to record continuously at a 200 kHz sampling rate. Along the Scotian Shelf off eastern Canada, recordings were made in the Gully, a prominent undersea canyon (42° 57′ N, 58° 60′ W) from March 17, 2010 to March 25, 2010 (8 days). At this site, an Autonomous Multichannel Acoustic Recorder (AMAR; JASCO Applied Sciences) was deployed at a depth of 1150 m, programmed to record continuously at a 384 kHz sampling rate.

2.2 Beaked whale detection and classification

Beaked whale echolocation signals were detected using a multistep process following the methods described in Baumann-Pickering *et al.* (2013). First, an automated detection algorithm was run through each full acoustic dataset to find echolocation clicks (Soldevilla *et al.*, 2008). To discriminate between delphinid and beaked whale clicks, criteria based on spectral and temporal characteristics were applied (see Baumann-Pickering *et al.*, 2013 for details). Clicks with peak and center frequencies of at least 32 and 25 kHz, respectively, durations of at least 355 μs, and frequency-modulated upsweeps with a sweep rate of at least 23 kHz/ms were considered potential beaked whale signals. The peak and center frequency thresholds were reduced to 23 kHz for the Gully dataset to detect clicks of northern bottlenose whales, *Hyperoodon ampullatus*. Due to a high level of false detections of non-beaked whale clicks after this initial discrimination step, an additional set of criteria was applied, requiring the waveform envelope of each click to increase over the first 0.1 ms and to remain above a 50% energy threshold for a duration of at least 0.1 ms. Clicks not meeting the criteria were removed from the analysis. The remaining clicks were grouped into detection events, defined as all consecutive beaked whale click trains separated by no more than 5 min. In a final classification step, each detected event was manually reviewed and assigned a species classification. Remaining false detections of non-beaked whale click events were removed from the analysis.

2.3 Subsampling analyses

To investigate the effects of using duty-cycled recordings to assess the daily presence of beaked whale echolocation signals, days with beaked whale detections in the continuous acoustic datasets were subsampled to simulate data collected at reduced recording schedules. Each recording schedule was defined by a duty cycle, representing the percent of time listening, and a cycle period duration in minutes, indicating the time between the start of one listening phase and the start of the next, repeated continuously throughout each day. Duty cycles of 50%, 25%, and 10% and cycle periods of 10, 20, 30, and 60 min were analyzed, for a total of 12 different recording schedules (Table 1).

To calculate a mean proportion of days ($\mathbf{P_d}$) for which daily presence was correctly assessed using each recording schedule, repeated subsampling was performed over each possible independent position of the duty cycle listening phase within the cycle period. For example, with a 50% duty cycle and 10 min cycle period, there are two possible independent, non-overlapping positions for the 5-min listening phase: 00:00–05:00 or 05:00–10:00. For each day *i* and listening phase position *j*, presence ($\boldsymbol{d}=1$) or absence ($\boldsymbol{d}=0$) of beaked whale detections in the subsampled data was determined, with presence defined as at least one detection event occurring within or overlapping with a listening phase. To calculate the mean proportion of days correctly assessed for beaked whale acoustic presence with a given recording schedule, the proportion of days with presence out of all $\boldsymbol{n}$ days with detections was averaged across all $\boldsymbol{p}$ listening phase positions

$$\overline{P_d} = \frac{1}{np}\sum_{j=1}^{p}\sum_{i=1}^{n} d_{i,j}. \qquad (1)$$

The standard deviation for each recording schedule was calculated across the $\boldsymbol{p}$ independent listening phase positions. The subsampling calculation in Eq. (1) was repeated with all 12 recording schedules for each beaked whale species in each dataset.

3. Results

3.1 Description of acoustic datasets

Five distinct beaked whale click types were identified within the recordings. Four of these have been previously attributed to specific species: Cuvier's (*Ziphius cavirostris*), Gervais' (*Mesoplodon europaeus*), and Blainville's (*M. densirostris*) beaked whales and northern bottlenose whales (e.g., Gillespie *et al.*, 2009; Johnson *et al.*, 2004; Wahlberg *et al.*, 2011; Zimmer *et al.*, 2005). The fifth click type is likely produced by Sowerby's beaked whales (*M. bidens*), based on similarities to clicks recorded in the presence of this species by Cholewiak *et al.* (2013) and known occurrence of Sowerby's beaked whales at the locations where this click type was recorded (Waring *et al.*, 2015; Whitehead, 2013). For simplicity, these clicks will be referred to as Sowerby's beaked whales throughout this paper. Table 2 provides a summary of the occurrence of each species within each full dataset. Multiple beaked whale species were detected at each recording site, with markedly different patterns in relative species occurrence among sites. The highest detection rates occurred at Cape Hatteras where Cuvier's beaked whales were detected most frequently. At Norfolk Canyon there were fewer beaked whale detections overall, and similar levels of occurrence of Sowerby's, Cuvier's, and Gervais' beaked whales. The Gully dataset, represented by a much smaller sample of recording days, contained detections of northern bottlenose whales and Sowerby's beaked whales at similar daily levels, but with more detections per day and longer detection durations for northern bottlenose whales.

Table 1. Recording schedules used for subsampling beaked whale detections. Each recording schedule is given as the number of minutes of listening time within each cycle period; cycle periods repeat continuously throughout each day.

	Cycle Period (minutes)			
Duty Cycle (%)	10	20	30	60
50	5 min	10 min	15 min	30 min
25	3 min[a]	5 min	8 min[a]	15 min
10	1 min	2 min	3 min	6 min

[a] Rounded up to the nearest full minute.

Table 2. Summary of beaked whale detections in the continuous acoustic datasets analyzed. Mean number of detections per day was calculated across all *n* days with at least one detection. The number of detected events per day and the detection duration are reported as the mean ± standard deviation.

Site	Species	# of days detected (*n*)	% of days detected	Mean # of detections/day	Mean detection duration (min)
Cape Hatteras (*N* = *289 days*)	*Z. cavirostris*	272	94	11.8 (±7.3)	7.3 (±7.5)
	M. europaeus	120	42	3.3 (±2.8)	5.5 (±5.5)
	M. densirostris	4	1	1.8 (±0.5)	3.2 (±3.0)
Norfolk Canyon (*N* = *289 days*)	*Z. cavirostris*	59	20	2.0 (±1.5)	7.6 (±6.5)
	M. europaeus	43	15	1.9 (±1.1)	6.0 (±5.0)
	M. bidens	103	36	1.9 (±1.3)	4.7 (±3.8)
The Gully (*N* = *8 days*)	*H. ampullatus*	6	75	7.0 (±2.3)	22.3 (±17.9)
	M. bidens	7	88	3.0 (±2.2)	6.6 (±3.7)

3.2 Subsampling comparisons

The effects of different recording schedules were compared by estimating the mean proportion of days correctly assessed for acoustic presence of each beaked whale species within each dataset. For all species at all sites, higher duty cycles (greater percent of time listening) resulted in higher proportions of days with a correct assessment (Fig. 1). Within a given duty cycle, shorter cycle periods consistently resulted in more days with a correct assessment. The effect of cycle period duration was most pronounced at the lowest duty cycles. For all but the most commonly detected species [Figs. 1(A) and 1(G)], a 10% duty cycle with a 60 min cycle period resulted in correct assessment of presence in approximately 30%–60% of days, while the same duty cycle with a 10 min cycle period resulted in correct assessment of presence in approximately 60%–95% of days [Figs. 1(B)–1(F), and Fig. 1(H)].

The degree to which daily presence was underestimated by subsampling varied among species and datasets. Subsampling had the largest effect on the probability of correctly assessing the daily presence of rarely detected species, and little to no effect on very commonly detected species, even at the lowest duty cycles. To investigate how low duty cycles differentially affected the assessment of presence among species within each dataset, a one-way analysis of variance (ANOVA) was used to examine differences in the mean proportion of days correctly assessed for each species after subsampling with a 10% duty cycle and a cycle period duration of 10, 20, 30, or 60 min. At Cape Hatteras, there was significant variation among species in the mean proportion

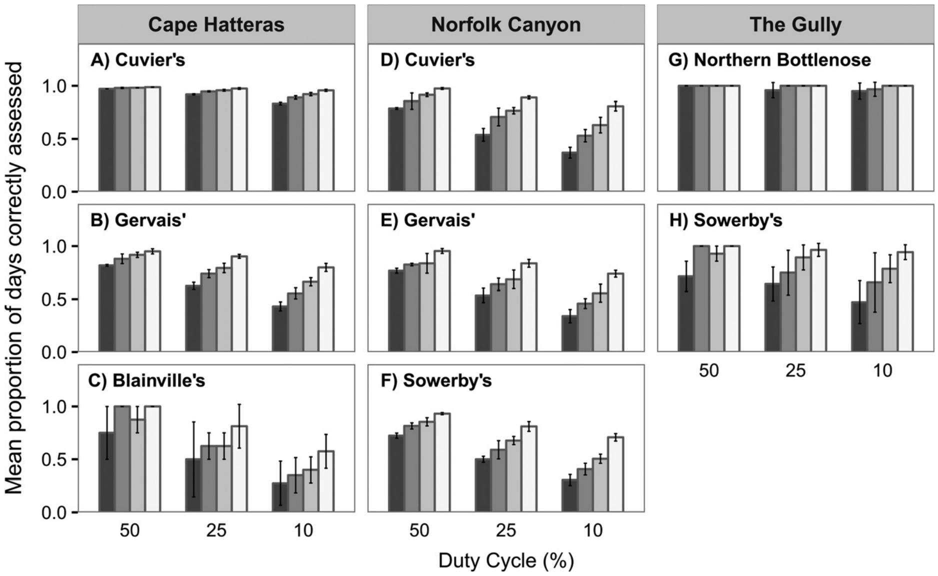

Fig. 1. Comparison of the mean proportion of days correctly assessed for beaked whale acoustic presence after subsampling. Error bars indicate standard deviation. Groups of bars represent duty cycle (% of time listening), and the individual bars in each group represent cycle periods of 60, 30, 20, and 10 min, from left (dark gray) to right (light gray).

of days correctly assessed using any cycle period duration (ANOVA, all p-values < 0.05). *Post hoc* Tukey HSD tests indicated that the proportion of days correctly assessed was significantly higher for Cuvier's beaked whales than either Gervais' or Blainville's beaked whales, and higher for Gervais' than Blainville's beaked whales at the $\alpha = 0.05$ level. At Norfolk Canyon, there was significant variation among species for cycle period durations of 10, 20, and 30 min (ANOVA, all p-values <0.05). Here, the proportion of days correctly assessed was significantly higher for Cuvier's than either Sowerby's or Gervais' beaked whales at the $\alpha = 0.05$ level, while assessment of presence of the two *Mesoplodon* species did not differ significantly. At the Gully site, the proportion of days correctly assessed was significantly higher for northern bottlenose whales than Sowerby's beaked whales across all cycle period durations (Welch's t-test, p-values <0.05).

4. Discussion

Predictably, any reduction in recording effort over a given monitoring period will lead to underestimation of species presence, except for those that are continuously present and acoustically active (Riera *et al.*, 2013; Thomisch *et al.*, 2015). The results presented here demonstrate that frequent, short listening periods provide a more accurate assessment of daily presence than longer, less frequent periods, even when the overall amount of recording effort is lower. Unlike many other marine mammal species, which may be detected over long distances for hours at a time, beaked whale clicks are only detected over relatively short ranges and durations, while the animal is foraging in close proximity to the recorder (Hildebrand *et al.*, 2015). Consequently, many beaked whale detections are likely to be missed if recordings are collected on a schedule where the cycle period duration greatly exceeds the average duration of detection events, which may be as short as a few minutes.

Assessment of the daily presence of beaked whales in subsampled recordings was strongly influenced by the underlying levels of acoustic activity of each species, which differed among locations. As beaked whale occurrence is spatially variable (e.g., Baumann-Pickering *et al.*, 2014), it is not possible to generate a broadly applicable correction factor for beaked whale presence in duty-cycled recordings collected at other locations. Nevertheless, it is worth noting that a consistent pattern was observed among species. At low duty cycles (10% listening time) the daily presence of *Mesoplodon* species was underestimated to a significantly greater degree than either Cuvier's beaked whales or northern bottlenose whales, across all three datasets examined. This result may be explained in part by the high number of detections per day of Cuvier's beaked whales and northern bottlenose whales at Cape Hatteras and the Gully, respectively, but the same pattern was found at Norfolk Canyon, where Cuvier's beaked whales did not occur more frequently than the other species (Table 2).

Cuvier's beaked whales and northern bottlenose whales exhibited longer mean detection durations than *Mesoplodon* species. This could reflect a greater number of individuals present, behavioral differences in dive depths and movement patterns of foraging animals, and/or acoustic characteristics of echolocation signals, such as frequency content, source level, and beam width (Shaffer *et al.*, 2013; Tyack *et al.*, 2006a; Zimmer *et al.*, 2008). The foraging and acoustic behavior of Cuvier's and Blainville's beaked whales have been reasonably well-studied (e.g., Baird *et al.*, 2006; Johnson *et al.*, 2008; Tyack *et al.*, 2006b), but there is little to no information available for many other beaked whale species, including Gervais' and Sowerby's beaked whales. Further data obtained from tagging studies may shed light on differences in acoustic detectability and help inform PAM efforts for these species.

Ultimately, recording schedules must be chosen to balance the scope and goals of the study with the capabilities of the recording system (Thomisch *et al.*, 2015). As technology continues to improve and data storage becomes less expensive, it is becoming feasible to collect continuous recordings over long deployment periods, even at high sampling rates. In cases where continuous monitoring is not practicable, a recording schedule based on short, frequent listening periods is recommended as the best choice for detecting beaked whales. However, it should not be assumed that all species will be equally under-sampled at the level of daily presence, as low duty cycles can lead to biased estimation of relative species occurrence. Whenever possible, duty-cycled recordings should be validated against continuous data collected within the same or similar regions where the same species of interest are detected. At a minimum, it is necessary to carefully consider the inferences drawn from duty-cycled recordings, particularly where these recordings provide the only available information on the relative occurrence of beaked whales and other poorly-known species.

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