Density and abundance of Cuvier's and Blainville's beaked whales in the Mariana Archipelago estimated using drifting acoustic recorders

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Project team:
Janelle Badger, Jennifer McCullough, & Erin Oleson, *Pacific Islands Fisheries Science Center*
Jay Barlow, contractor for *Cascadia Scientific Services*
Robin W. Baird, *Cascadia Research Collective*
Taiki Sakai, contractor for *Southwest Fisheries Science Center*

Introduction

NOAA Fisheries Science Centers have increasingly relied on passive acoustic datasets to augment traditional visual-based assessment efforts. Both Southwest and Pacific Islands Fisheries Science Centers have recently incorporated drifting acoustic spar buoy recorders (DASBRs) into their standard large-scale survey designs. Drifting autonomous instruments have many advantages, especially for species that are difficult to see at the surface, are vocal at depth, and whose sounds have been well characterized such that they can be readily identifiable from autonomous recordings. In the Pacific Islands, drifting recorder data formed the basis of a recent study on habitat preferences of deep-diving beaked whales and *Kogia* species (McCullough et al 2021a). Substantial investment in the statistical treatment of these datasets for beaked whales led to the first-ever acoustic-based density and abundance estimates for Cuvier's beaked whales along the entire US west coast (Barlow et al 2021a).

The Pacific Marine Assessment Program for Protected Species (PacMAPPS) is a multi-agency (National Marine Fisheries Service, Navy, Bureau of Ocean Energy Management) initiative that supports cetacean surveys in regions of joint interest. In 2021 the Navy supported line-transect surveys for cetaceans throughout the Guam and Commonwealth of the Northern Mariana Islands (CNMI) exclusive economic zones (EEZs), a project known as the Mariana Archipelago Cetacean Surveys (MACS). As with other recent large-scale survey efforts, Pacific Islands Fisheries Science Center (PIFSC) deployed DASBRs throughout the survey region with the goal of collecting data on the occurrence of beaked whales and other cryptic deep-divers. Traditional line-transect assessments for those species are often challenged by very low encounter rates, resulting in density and abundance estimates with high uncertainty, or in some cases, no estimates if groups were not seen during the 'on-effort' portions of the survey. Previous experience in the Marianas suggested that encounter rates for beaked whales on the DASBRs would be orders of magnitude higher within the DASBR data than in the visual survey or towed array datasets, likely enabling examination of density for some beaked whale species using the newly developed methods of Barlow et al. (2021a).

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6. AUTHOR(S)
Janelle Badger
Jay Barlow
Robin Baird
Taiki Sakai

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Pacific Islands Fisheries Science Center, NOAA Fisheries, Honolulu, Hawaii
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14. ABSTRACT

NOAA Fisheries Science Centers have recently incorporated drifting acoustic spar buoy recorders (DASBRs) into their standard large-scale survey designs. Drifting autonomous instruments have many advantages, especially for species that are difficult to see at the surface, are vocal at depth, and whose sounds have been well characterized such that they can be readily identifiable from autonomous recordings. Pacific Islands Fisheries Science Center deployed DASBRs throughout the survey region with the goal of collecting data on the occurrence of beaked whales and other cryptic deep-divers. Traditional line-transect assessments for those species are often challenged by very low encounter rates, resulting in density and abundance estimates with high uncertainty, or in some cases, no estimates if groups were not seen during the 'on-effort' portions of the survey. Previous experience in the Marianas suggested that encounter rates for beaked whales on the DASBRs would be orders of magnitude higher within the DASBR data than in the visual survey or towed array datasets, likely enabling examination of density for some beaked whale species using the newly developed methods of Barlow et al. (2021a). Here, we detail our methodology to estimate density and abundance using 2021 survey dataset and how 2018 survey data were used to inform the detection parameters. This analysis has resulted in the first preliminary acoustic density and abundance estimates for Cuvier's and Blainville's beaked whales in the Mariana Islands region.

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At the completion of the MACS 2021 survey, additional funds were available from the Navy to pursue density and abundance estimates for Cuvier's and Blainville's beaked whales using the DASBR dataset. Here, we detail our methodology to estimate density and abundance using the 2021 dataset and how the 2018 data were used to inform the detection parameters.

Methods

Data collection

DASBRs consist of a vertical hydrophone array with two hydrophones spaced 10 m apart and centered at 150m depth. The recorders are deployed from the ship during standard visual survey operations and left to drift for 2-25 days before their recovery, aided by an Iridium tracker within the buoy's surface float. PIFSC has deployed DASBRs during four large-scale surveys since 2017, two in the main Hawaiian Islands and two in the Mariana Archipelago (McCullough et al., 2021a,b; Yano et al., 2018, 2020, 2022). The details of the DASBR configuration and deployment location and duration during Mariana Archipelago surveys are found in Hill et al. (2020), McCullough et al. (2021a), and Yano et al. (2022). Most notably there was a vast difference in study area sizes between 2018 and 2021 due to available ship time, resources, and effort. In turn the 2018 survey worked as a pilot study for the efforts conducted in 2021. Acoustic data were recorded in 2018 at 288 kHz sampling rate and duty cycle of 2 minutes on, 3 minutes off, and in 2021 with a 384 kHz sampling rate and duty cycle of 2 minutes on, 8 minutes off.

The 2018 DASBR dataset (n=8, Figure 1, Appendix 1) from deployments west of the island chain was used to provide additional data from the study area needed to derive parameter estimates or examine sensitivity in those estimates. The MACS 2021 effort provided data from 21 DASBRs deployed throughout the Guam and Commonwealth of the Northern Marianas EEZ (Figure 2, Appendix 1). We further assessed the possibility that our drifting acoustic recorders get entrained in oceanographic features that may have greater or lesser beaked whale density, violating the assumption of random sampling. We conducted a simple analysis to investigate this possibility by modeling the within-drift detection rate as a function of time since the drift was deployed using a generalized additive model (see Appendix 2), and found no evidence of non-random sampling.

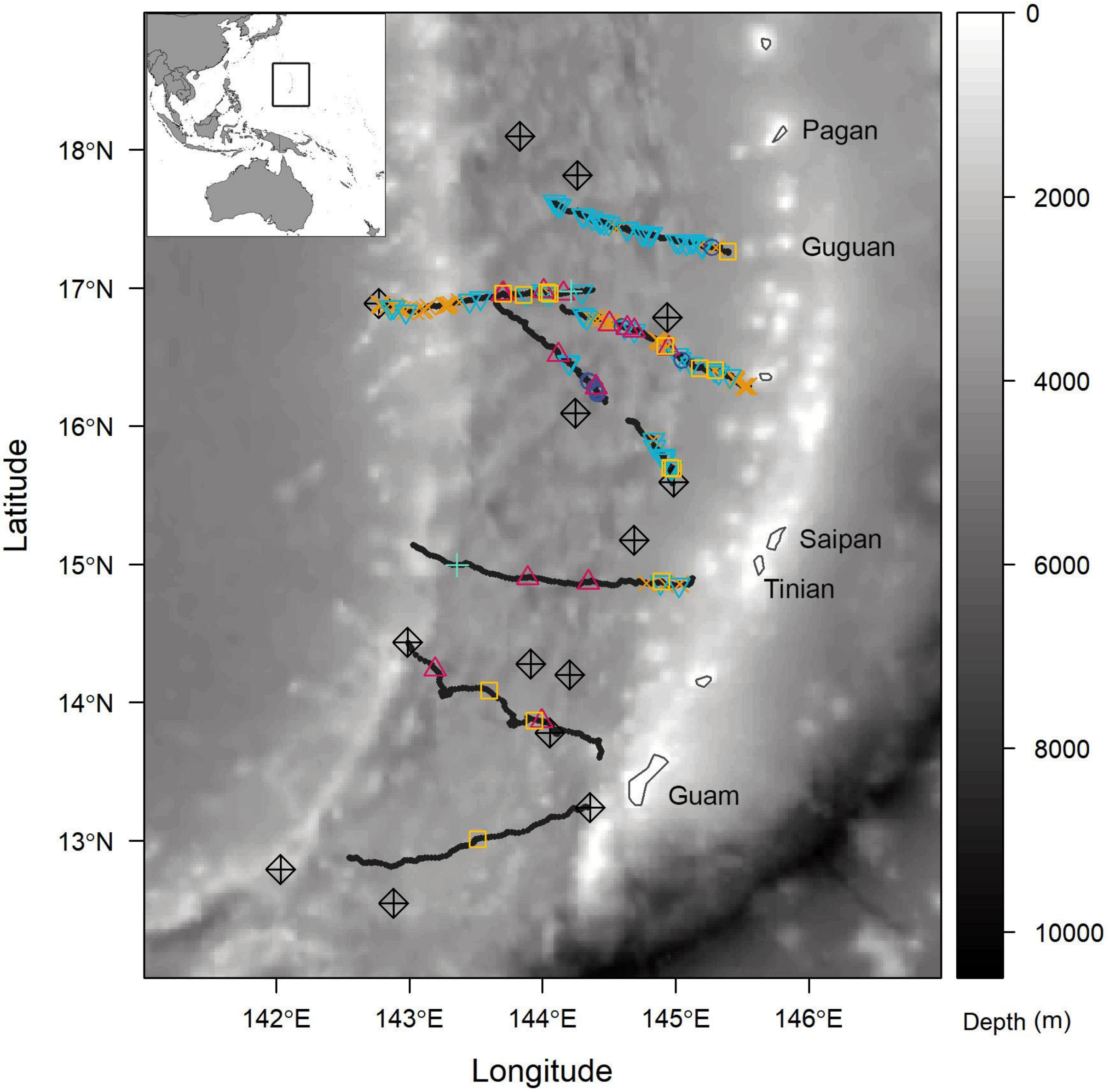

Figure 1. Maps of DASBR tracks and beaked whale detections in 2018. The 2018 map is extracted from McCullough et al (2021a), with consistent symbols for Cuvier's and Blainville's beaked whale all maps in this report. (Blainville's = blue downward triangle; Cuvier's = orange "x"; Longman's = purple circle; BWC = yellow square; Kogia spp. = pink upward triangle; unknown BW = teal cross).

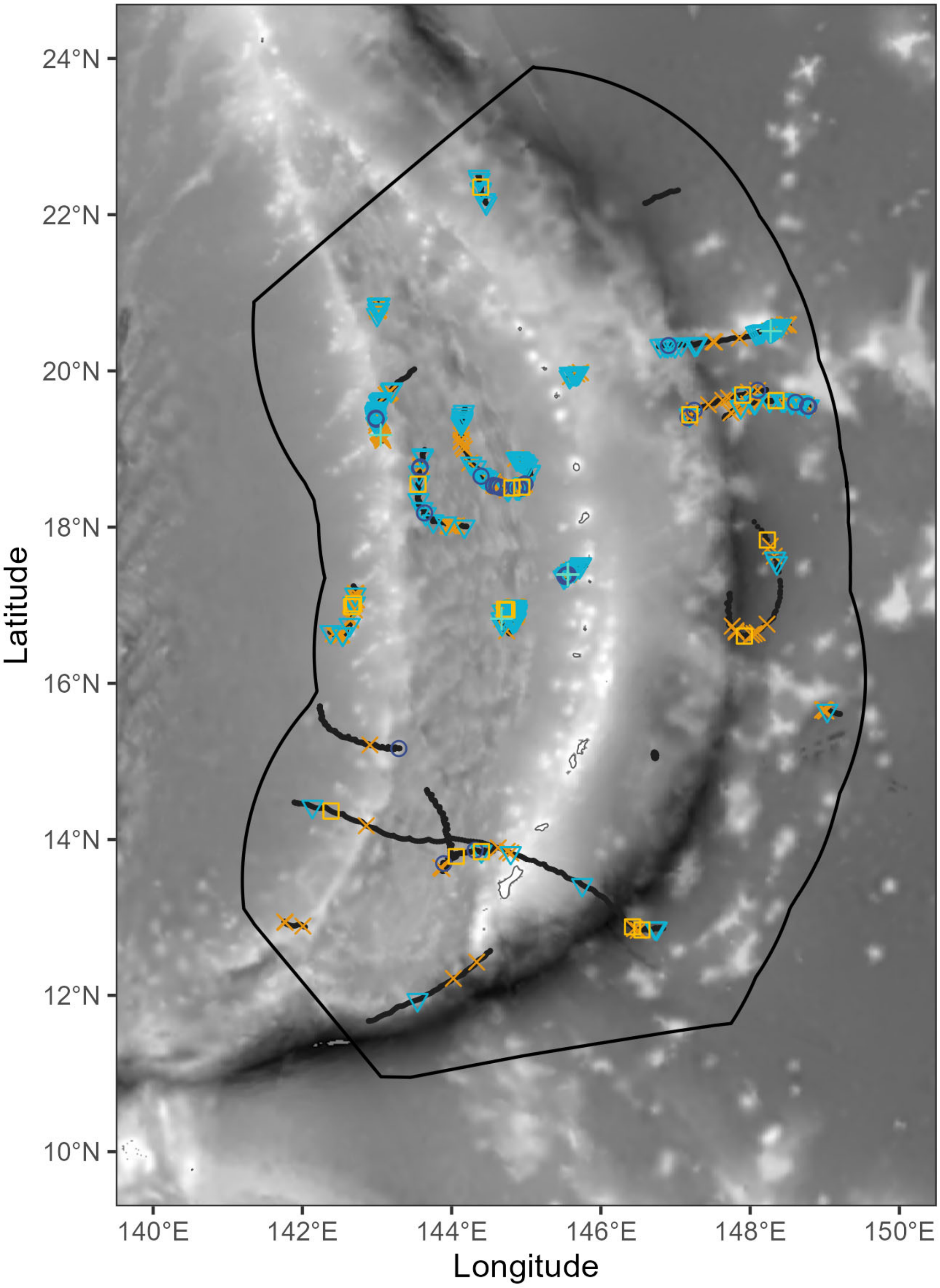

Figure 2. Map of DASBR tracks and beaked whale detections in 2021 (Blainville's = blue downward triangle; Cuvier's = orange "x"; Longman's = purple circle; BWC = yellow square; Kogia spp. = pink upward triangle; unknown BW = teal cross). The combined EEZ for the Commonwealth of the Northern Marianas and Guam is shown on the map in black.

DASBR data processing

The detailed acoustic data processing approach is provided in Barlow et al. (2021a) and is only summarized here. A semi-automated approach was used to detect beaked whales within the 2018 and 2021 DASBR datasets. Acoustic data files were processed using PAMGuard software (version 2.01.05; Gillespie et al., 2009) to detect echolocation pulses using the Click Detector module (IIR Butterworth 4 kHz high pass filter) and to classify those pulses based on peak frequencies and the presence of a frequency change (upsweeps). Vertical bearing angles were estimated from the time-difference-of-arrival of the same echolocation click on the upper and lower hydrophones using the cross-correlation algorithm in PAMGuard. To identify beaked whale echolocation pulses, analysts reviewed the pulse detections in the time-bearing display within PAMGuard Viewer software. All potential beaked whale encounters were identified based on four criteria: peak frequency, duration, having a downward bearing angle that remains relatively constant, and the frequency contour, which is generally upsweeping for beaked whales (e.g. Baumann-Pickering et al. 2014). Surface reflections are occasionally present for beaked whale signals and can aid in discriminating beaked whales from dolphins. Detections identified as beaked whales were then manually classified to species using published acoustic signal characteristics (Baumann-Pickering et al. 2013 & 2014, Keating et al. 2016).

Acoustic detections classified as Cuvier's or Blainville's beaked whales were included in the density analysis if at least three pulses at the same bearing angle met the established criteria. The number of detections of each species in each DASBR survey year are reported based on the number of 2-minute data files with each species present (Table 1). The detection locations are shown in Figures 1 & 2.

Table 1. Number of DASBR drifts during MACS 2018 and MACS 2021 surveys, and the number of 2-minute recording files with detections of Cuvier's and Blainville's beaked whales.

Year	DASBR drifts analyzed	# Cuvier's beaked whale detections	# Blainville's beaked whale detections
2018	8	175	203
2021	21	335	395

Density estimation

The population density of Cuvier's and Blainville's beaked whales was estimated using a group-based, point-transect analysis in a Bayesian framework following Barlow et al. (2022). Sampling intervals are equal to the file recording length (2 min). We summarize the process of the derivation of the density estimator here. Further details are provided in Barlow et al. (2022), although we adapted this method to better suit both our focal species in the Marianas. For each species, the expected number of snapshots (i.e., 2-min files) with groups detected on each drift i, n_i, ∈ 1,…, j total drifts is given by the fraction:

$$E[n_i] = \frac{D_i \cdot k_i \cdot \hat{v} \cdot \hat{\lambda}}{\hat{s}_i}$$

where D_i is the density of beaked whales at drift *i*, k_i is the number snapshots in drift *i*, $\hat{v}$ is the estimated area effectively surveyed, $\hat{\lambda}$ is the estimated probability the group available for detection within a snapshot, and $\hat{s}$ is the estimated mean group size for drift *i*.

The number of snapshots with group detections is modeled as a Poisson variable, i.e.,

$$n_i \sim Poisson(E[n_i])$$

and group densities G_i are defined as:

$$G_i = \frac{D_i}{\hat{s}_i}.$$

Available-group densities (not yet corrected for availability) are modeled as random effects, such that:

$$log\, log\, (G_i) = \theta + \varepsilon_i$$

where θ is the mean log(group density) over the study area, and

$$\varepsilon_i \sim Normal(0, \sigma_G^2).$$

Then, density of available animals on each drift is given by:

$$D_i = G_i \cdot \hat{s}_i$$

and the density of animals in the study area (correcting for availability) is:

$$\underline{D} = \frac{1}{j \cdot \hat{\lambda}} \sum_{i=1}^{j} D_i.$$

The area effectively surveyed, $\hat{v}$, was estimated by fitting a compound half-normal detection function (the probability of detection as a function of range) that, using a species-specific echolocation depth distribution (see below), best simulates the observed distribution of vertical detection angles. This detection function was fit using a maximum simulated likelihood approach (for further details see Barlow et al. 2022). While this method assumes that detection is certain at zero absolute distance from the hydrophone, it does not require the assumption that detection is certain at zero horizontal range. This process was implemented in R (R Core Team 2022) prior to the Bayesian modelling step.

The probability that a group is available for detection within a snapshot, $\hat{\lambda}$, was calculated as the fraction of a complete foraging dive cycle during which a group is acoustically active and available to be detected by our hydrophone system. The numerator of this fraction was estimated using a Cormack-Jolly-Seber mark-recapture model where group detections were expressed as a capture history of intervals equal to the snapshot length, 2 min. The survival rate parameter from the CJS model was used to calculate the mean "lifespan" (in terms of the number of intervals/snapshots) that the encounter is available to be detected (i.e., "alive") using life-table methods (Barlow et al. 2021b, Barlow et al. 2022). To calculate $\hat{\lambda}$, this lifespan is then divided by the duration of dive cycle (see below), defined as the time between the start of successive dives. The mark-recapture model was incorporated into the Bayesian density estimation framework such that the variation in availability time was appropriately propagated to our estimates of $\hat{\lambda}$.

Density estimates were then extrapolated to estimate study area abundance, *N*. The study area was defined a-priori to be the U.S. EEZ surrounding Guam and CNMI. However, acoustic survey effort did not effectively cover some regions of that study area in the south and north, so a smaller *a-posteriori* study area was defined by a minimum convex polygon that covered all survey effort plus a 50 km buffer (R packages *sf*, Pebemsa 2018; *terra*, Hijmans 2023; R Core Team 2022). The area of this region is 838,392.9 km^2. Previous analysis of these data, as well as our own observations of detection rates, suggests strong latitudinal variation in beaked whale occurrence in the Marianas (McCullough et al. 2021a), so we divided our study area into northern and southern strata demarcated at 15.5°N (Figure 3). The areas of these strata are 500,520.6 km^2 and 337,872.3 km^2 for the northern and southern regions, respectively. For each species, density estimation was undertaken for each strata, then extrapolated to estimate each strata's abundance, and finally the strata-specific abundance posterior distributions were summed to estimate total study area abundance.

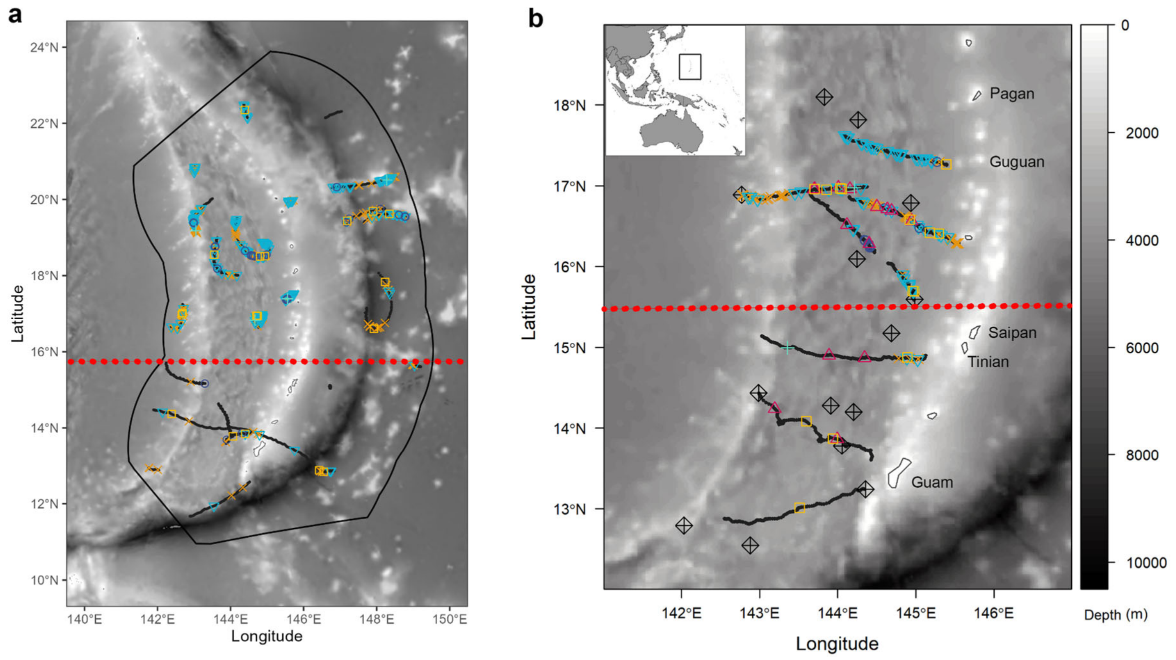

Figure 3. Maps of 2021 (a) and 2018 (b) MACS study areas with the red dotted line indicating the northern and southern strata demarcated at 15.5°N.

Ancillary data

Ancillary data were required to formulate some of the parameters in the density estimation framework. Specifically, estimating the probability of detection relies on assessment of dive cycle duration (for animal availability) and echolocation depths (for the detection function with range) derived from time-depth tags deployed on each focal species. As there are no tag data available from the Mariana Archipelago, datasets from other regions, including Hawaiʻi, the Bahamas, southern California, North Carolina, the Ligurian Sea, the Azores, and other areas were gathered to examine the sensitivity in these measurements to geographic location, tag type, and individual variation to generate appropriate values for use in the Marianas (Barlow et al., in prep). Dive cycle duration estimates from previous DASBR deployments (Barlow & McCullough 2022) are also used to inform this parameter.

Given the very low number of beaked whale sightings in the Marianas, mean group size was informed using group size data from visual sightings of each species within the study area and from small boat (Baird et al. 2019, Yano et al. 2022) and NMFS large-vessel abundance surveys throughout the central and western Pacific. We constructed a lognormal prior distribution for mean group size based on the mean and standard error of the observed group sizes. Because there was high variation in observed group sizes in the central Pacific, we introduced some variation to the group size element of the density estimator by drawing a mean group size for each drift from the prior distribution, rather than one mean group size applied to all drifts as was done in Barlow et al. (2022).

Model fitting and diagnostics

Model fitting was implemented in the R environment in two stages: (1) the maximum simulated likelihood model to estimate $\hat{\nu}$ and the detection function and (2) the Bayesian model, which was comprised of the mark-recapture model to estimate availability and our group-based point-transect model to estimate density. We evaluated the performance of our maximum simulated likelihood approach by comparing our observed detection angle distribution with the distribution of predicted angles generated from the estimated detection function using K-S tests.

The Bayesian model was fit using the R package rjags (Plummer 2022). We ran 3 chains for 200,000 iterations, discarding the first 50,000 iterations as burn-in, and then retaining one out of every 5 samples for a total of 90,000 samples used for inference. For the mark-capture portion of the Bayesian model, uninformative Beta(1,1) priors were used for ϕ (survival rate parameter) and p (nuisance parameter). For the population model, priors for parameters describing the log density of groups (σ_G , θ) were uninformative ($\theta \sim Normal(0, 0.001)$, $\sigma_G \sim Unif(0,4)$, respectively). Group sizes $\hat{s}_i$ were drawn from species-specific mean group size priors. The mean and SE of observed group sizes for Cuvier's and Blainville's beaked whales were 2.45 $\pm$ 0.13 and 4.07 $\pm$ 0.25, corresponding to LogNormal(0.887, 0.134) and LogNormal(1.402, 0.061) priors, respectively. The prior for dive cycle duration (in minutes) was informed by our ancillary data and determined to be Normal(152.06, 27.45) and

Normal(145.28, 25.13) for Cuvier's and Blainville's beaked whales, respectively, and truncated to positive values (> 0). The prior for effective survey area, $\hat{v}$, was Normal given parameters from the maximum simulated likelihood modeling stage. We measured MCMC chain convergence using the potential scale reduction factor $\hat{R}$, where a $\hat{R}$ value close to 1.0 (< 1.1) indicates adequate convergence of posterior chains.

Results

It was not possible to estimate density for the 2018 survey area due to a lack of model convergence, however, we improved the estimation of the 2021 detection function by including detection angles from 2018. The following results refer to beaked whale encounter data from 2021.

Overall, Blainville's beaked whales have a much higher estimated density and consequently a larger abundance than Cuvier's in the Mariana Archipelago (Tables 2 and 3). Our estimated abundance of our focal species in the study area is 6,001 (95% credible interval (CRI): [3,904; 8,605]) Cuvier's beaked whales and 15,667 (95% CRI: [10,144; 22,096]) Blainville's beaked whales (Tables 2 & 3, Figures 4 & 5). The substantial difference in density between Cuvier's and Blainville's beaked whales is attributable to both differences in encounter rates consistent across strata (Table 2) and the larger and more variable Blainville's group sizes. In our analysis of group sizes from visual encounters in the Marianas and Hawai'i, Cuvier's group sizes averaged 2.45 ($\pm$ 1.36 SD) while Blainville's beaked whales averaged 4.07 ($\pm$2.32 SD), corresponding to a smaller and much narrower mean group size prior distribution for Cuvier's than for Blainville's (Figure 6). Within species, the latitudinal difference in encounter rate translated to substantial differences in density and abundance. Cuvier's beaked whales were detected almost 2x more often in the northern vs. southern strata, and Blainville's beaked whales were detected almost 7x more often in the northern strata (Table 2). The U.S. Marine Mammal Protection Act defines allowable takes (potential biological removal or PBR) based on a minimum estimate of abundance, Nmin. Operationally, this minimum has been defined as the 20th percentile of the posterior distribution for N; Nmin is 4,984 for Cuvier's beaked whales and 13,099 for Blainville's beaked whales.

The compound half normal detection function yields effective detection radii (EDR) estimates of 3.75 km and 3.29 km, and effective survey areas, $\hat{v}$, of about 44.4 km^2 and 34.1 km^2, respectively, for Cuvier's and Blainville's beaked whales (Tables 2 and 3). Our K-S tests do not indicate a lack of fit (p = 0.21 for Blainville's and p = 0.39 for Cuvier's). In our Bayesian model, there was no evidence for a lack of convergence, with all $\hat{R}$ values close to 1.0.

Table 2. Model results for Bayesian model estimating density of Cuvier's beaked whales in the Mariana Archipelago. A-posteriori study areas of 500,521 km^2 and 337,872 km^2 for the northern and southern regions were used for abundance estimates.

Species (Strata)	Parameter	Posterior Mean	Posterior SD	95% CRI	$\hat{R}$
Cuvier's beaked whales (North)	Density (individuals per 1000 km^2)	8.72	1.99	[5.21, 13.0]	1.0
	Abundance, *N* (rounded)	4,365	993	[2,614; 6,511]	1.0
Mean percent of snapshots with group detections = 1.89%	$\hat{\lambda}$	0.125	0.026	[0.088, 0.187]	1.0
	Effective search area, $\hat{v}$ (km^2)	44.4	4.30	[36.3, 53.2]	1.0
	Mean time available (minutes)	18.3	0.734	[16.7, 19.6]	1.0
	Dive cycle duration (minutes)	152.0	27.6	[97.9, 206.2]	1.0
Cuvier's beaked whales (South)	Density (individuals per 1000 km^2)	4.78	1.97	[1.99, 9.57]	1.0
	Abundance, *N* (rounded)	1,642	670	[694; 3,270]	1.0
Mean percent of snapshots with group detections = 0.84%	$\hat{\lambda}$	0.098	0.026	[0.095, 0.160]	1.0
	Effective search area, $\hat{v}$ (km^2)	44.4	4.31	[36.2, 53.2]	1.0
	Mean time available (minutes)	14.5	2.51	[9.8, 19.4]	1.0
	Dive cycle duration (minutes)	152.0	27.5	[98.0, 206.1]	1.0
Total Cuvier's beaked whale abundance in study area		6,001	1,199	[3,904; 8,605]	

Table 3. Model results for Bayesian model estimating density of Blainville's beaked whales in the Mariana Archipelago. A-posteriori study areas of 500,521 km^2 and 337,872 km^2 for the northern and southern regions were used for abundance estimates.

Blainville's beaked whales (North)	Density (individuals per 1000 km^2)	28.5	5.89	[17.8, 41.0]	1.0
	Abundance, *N* (rounded)	14,258	2964	[8,882; 20,560]	1.0
Mean percent of snapshots with group detections = 3.06%	$\hat{\lambda}$	0.132	0.025	[0.0897, 0.175]	1.0
	Effective search area, $\hat{v}$ (km^2)	34.1	2.55	[29.3, 39.2]	1.0
	Mean time available (minutes)	18.5	0.613	[17.2, 19.6]	1.0
	Dive cycle duration (minutes)	145.2	25.1	[95.7, 194.0]	1.0
Blainville's beaked whales (South)	Density (individuals per 1000km^2)	4.15	2.05	[1.46, 9.25]	1.0
	Abundance, *N* (rounded)	1,447	713	[510; 3,223]	1.0
Mean percent of snapshots with group detections = 0.37%	$\hat{\lambda}$	0.112	0.031	[0.061, 0.182]	1.0
	Effective search area, $\hat{v}$ (km^2)	34.1	2.55	[29.3, 39.3]	1.0
	Mean time available (minutes)	15.6	3.18	[9.09, 22.7]	1.0
	Deep dive period (minutes)	145.2	25.1	[95.6, 193.8]	1.0
Total Blainville's beaked whale abundance in study area		15,667	3,044	[10,144; 22,096]	

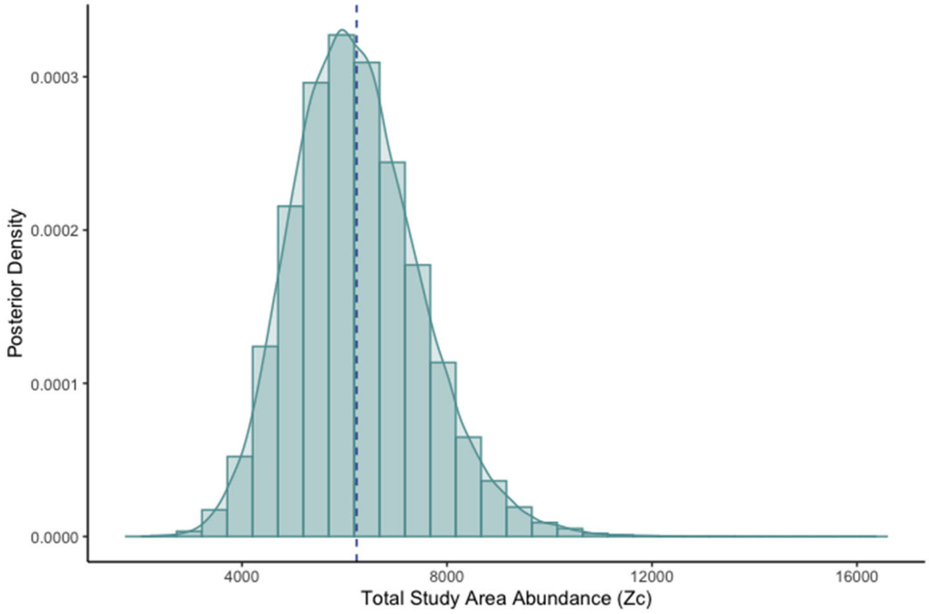

Figure 4. Posterior density of Cuvier's beaked whale abundance in the Mariana Archipelago. Dashed line represents posterior mean.

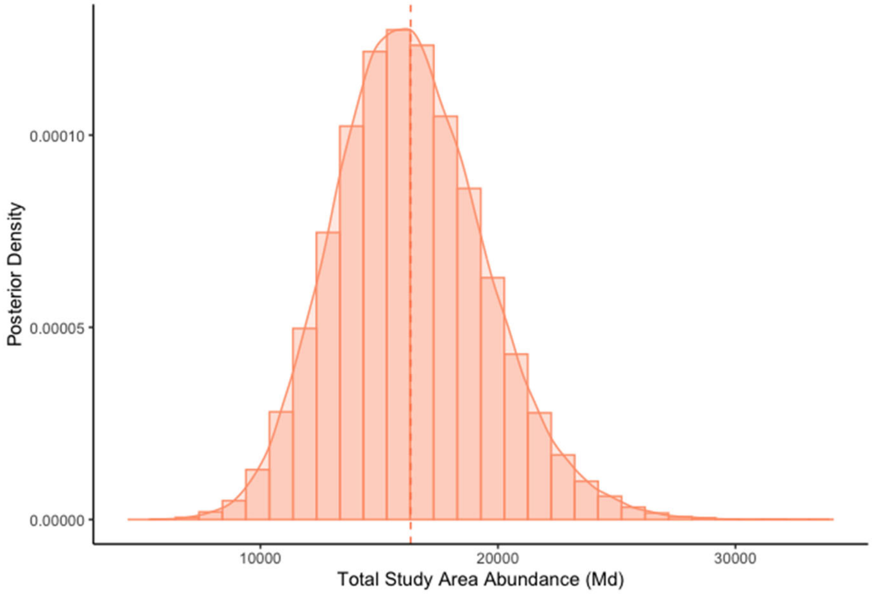

Figure 5. Posterior density of Blainville's beaked whale abundance in the Mariana Archipelago. Dashed line represents posterior mean.

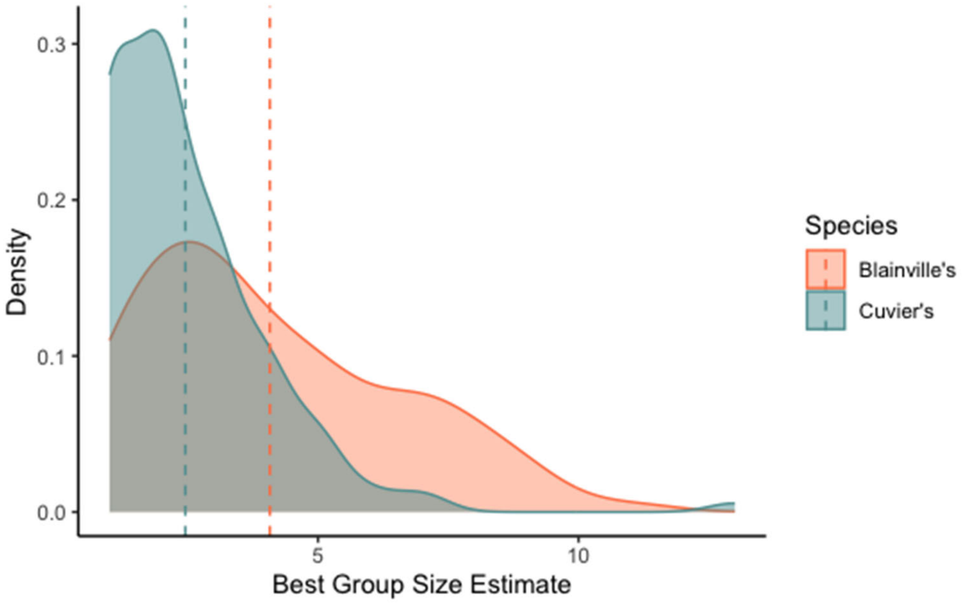

Figure 6. Observed group sizes from beaked whale encounters during visual surveys in Hawai`i and the Mariana Archipelago. Dashed lines represent the mean.

Conclusions

Here, we provide the first density estimates of Cuvier's and Blainville's beaked whales in the Marianas using recent developments in the statistical treatment of acoustic data collected on drifting recorders. Due to the long dives of beaked whales and typical high sea states of offshore surveys, visual sightings are rare, making traditional density estimation difficult, imprecise, or sometimes unachievable.

Our framework required a few key assumptions. First, we assume that there are no false positive detections of Cuvier's or Blainville's beaked whales due to manual verification of species identification. Second, we assume that the density of our focal species is random with respect to drift sampling. While the results of our approach to address this issue do not indicate non-random sampling of DASBRs, there was high variability in model results across drifts so our interpretation is inconclusive.

While it may be possible to explore an approach utilizing both datasets, this will require careful thought. The 2018 DASBR drifts are much more restricted geographically (Figure 1) and concentrated in an area with a high density of drifts in 2021 (Figure 2). As our density estimation framework is not a spatial model and so does not account for spatial autocorrelation, and thus only treats each drift's density as a random effect, this intensely surveyed area would have a large effect on resulting density estimates. Further development of visual spatial density models currently in progress could integrate these acoustic data to improve estimates while accounting for spatial autocorrelation.

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Literature Cited

Baird, R. W. (2019). Behavior and ecology of not-so-social odontocetes: Cuvier's and Blainville's beaked whales. In B. Würsig (Eds.), *Ethology and Behavioral Ecology of Odontocetes* (pp 305-329). Basel, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-030-16663-2

Barlow, J., McCullough J.L.K. (2022). Beaked whale dive cycle estimation based on acoustic data from drifting recorder systems. Marine Mammal Science https://doi.org/10.1111/mms.12987

Barlow, J., Moore, J.E., J.L.K. McCullough, E.T. Griffiths. (2022). Acoustic-based estimates of Cuvier's beaked whale (*Ziphius cavirostris*) density and abundance along the U.S. west coast from drifting hydrophone recorders. Marine Mammal Science 38(2): 517-538. https://doi.org/10.1111/mms.12872

Barlow, J., Fregosi, S., Thomas, L., Harris, D., & Griffiths, E. T. (2021a). Acoustic detection range and population density of Cuvier's beaked whales estimated from near-surface hydrophones. Journal of the Acoustical Society of America, 149(1), 111–125. https://doi.org/10.1121/10.0002881

Barlow, J., Trickey, J. S., Schorr, G. S., & Moore, J. E. (2021b). Recommended snapshot length for acoustic point-transect surveys of intermittently available beaked whales. *Journal of the Acoustical Society of America*, 149, 3830– 3840. https://doi.org/10.1121/10.0005108

Baumann-Pickering, S., McDonald, M. A., Simonis, A. E., Solsona Berga, A., Merkens, K. P., Oleson, E. M., Roch, M. A., Wiggins, S. M., Rankin, S., Yack, T. M., & Hildebrand, J. A. (2013). Species-specific beaked whale echolocation signals. *Journal of the Acoustical Society of America*, 134(3), 2293-2301. https://doi.org/10.1121/1.4817832

Baumann-Pickering, S., Roch, M. A., Brownell, R. L., Jr., Simonis, A. E., McDonald, M. A., Solsona-Berga, A., Oleson, E. M., Wiggins, S. M., Hildebrand, J. A. (2014). Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific. *PLoS One*, 9(1), e86072. http://doi.org/10.1371/journal.pone.0086072

Fiedler, P.C., Becker, E.A., Forney, K.A., Barlow, J. Moore, J.E. (2023) Species distribution modeling of deep-diving cetaceans. Marine Mammal Science 39(4): 1178-1203. https://doi.org/10.1111/mms.13057

Hijmans, R. (2023). terra: Spatial Data Analysis. R package version 1.7.3, https://CRAN.R-project.org/package=terra.

Hill, M.C., Oleson, E.M. Bradford, A.L., Martien, K.K. Steel, D., Baker, C.S. (2020) Assessing cetacean populations in the Mariana Archipelago: A summary of data and analyses arising from Pacific Islands Fisheries Science Center surveys from 2010–2019. NOAA technical Memorandum NMFS-PIFSC- 108. https://doi.org/10.25923/wrye-6h14.

Keating, J. K., Barlow, J., & Rankin, S. (2016). Shifts in frequency-modulated pulses recorded during an encounter with Blainville's beaked whales (*Mesoplodon densirostris*). *Journal of the Acoustical Society of America*, 140(2), EL166-EL171. https://doi.org/10.1121/1.4959598

McCullough, J.L.K, Wren, J.L.K, Oleson, E.M., Allen, A.N., Siders, Z.A., Norris, E.S. (2021a) An Acoustic survey of beaked whales and *Kogia* spp. in the Mariana archipelago using drifting recorders. Frontiers in Marine Science 8:664292. https://doi.org/10.3389/fmars.2021.664292

McCullough, J. L. K., Oleson, E. M., Barlow, J., Allen, A. N., & Merkens, K. P. (2021b). An acoustic survey in the main Hawaiian Islands using drifting recorders. NOAA Administrative Report H-21-04. National Marine Fisheries Service. https:// doi.org/10.25923/rzzz-0v38

Pebesma E (2018). Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal, **10**(1), 439–446. https://doi.org/10.32614/RJ-2018-009.

Plummer M (2022). rjags: Bayesian Graphical Models using MCMC. R package version 4.13,

https://CRAN.R-project.org/package=rjags.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Yano, K.M., Hill, M.C., Oleson, E.M., McCullough, J.L.K. Henry, A.E. (2022) Cetacean and Seabird Data Collected During the Mariana Archipelago Cetacean Survey (MACS), May–July 2021. NOAA Technical Memorandum NMFS-PIFSC- 128. https://doi.org/10.25923/7pbh-zq68

Yano, K. M., Oleson, E. M., Keating, J. L., Ballance, L. T., Hill, M. C., Bradford, A. L., Allen, A. N., Joyce, T. W., Moore, J. E., & Henry, A. (2018). Cetacean and seabird data collected during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS), July–December 2017. NOAA Technical Report NMFS-PIFSC-72. U.S. Department of Commerce. https:// doi.org/10.25923/7avn-gw82

Yano, K. M., Oleson, E. M., McCullough, J. L. K., Hill, M. C., & Henry, A. E. (2020). Cetacean and seabird data collected during the Winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (Winter HICEAS), January–March 2020. NOAA Technical Report NMFS-PIFSC-111. U.S. Department of Commerce. https://doi.org/10.25923/ehfg-dp78

Appendix 1: Deployment/retrieval locations and dates of drifting acoustic recorders, DASBRs, during MACS 2018 & 2021.

	DEPLOYMENT			**RETRIEVAL**			
ID	LAT (°N)	LON (°E)	Time (UTC)	LAT (°N)	LON (°E)	Time (UTC)	Duration (h:mm:ss)
DS1	13.60	144.43	7/09/2018 08:13:06	14.43	142.99	7/20/2018 08:43:10	264:41:59
DS2	14.90	145.13	7/09/2018 18:10:54	15.14	143.03	7/20/2018 20:49:14	266:49:30
DS3	16.29	145.54	7/11/2018 12:14:40	16.86	144.15	7/24/2018 00:26:27	275:25:38
DS4	17.26	145.40	7/12/2018 14:34:54	17.63	144.09	7/24/2018 05:58:33	279:50:49
DS5	16.98	144.38	7/14/2018 16:12:47	16.88	142.77	7/22/2018 20:50:37	208:14:27
DS6	16.17	144.47	7/15/2018 06:47:55	16.89	143.65	7/23/2018 20:48:10	206:11:07
DS7	13.24	144.36	7/18/2018 09:12:23	12.88	142.55	7/27/2018 02:33:13	209:32:21
DS8	15.58	144.98	7/21/2018 09:04:31	16.04	144.65	7/25/2018 19:37:05	107:06:16
DS1	13.85	144.56	5/03/2021 08:47:28	14.67	143.67	5/28/2021 12:00:43	285:19:09
DS3	17.31	145.47	5/06/2021 08:43:05	17.52	145.79	5/11/2021 06:41:27	118:40:15
DS4	19.53	144.18	5/08/2021 19:56:40	18.87	144.86	5/25/2021 12:47:02	389:03:37
DS5	16.64	144.78	5/11/2021 20:04:47	16.78	144.82	5/25/2021 06:52:10	335:14:40

DS6	15.17	143.31	5/12/2021 10:20:31	15.71	142.24	5/26/2021 21:32:12	347:22:16
DS7	16.66	142.38	5/16/2021 10:24:46	17.24	142.68	5/26/2021 10:31:17	240:41:07
DS8	18.99	143.64	5/17/2021 09:45:45	18.01	144.20	5/25/2021 10:46:17	193:14:18
DS9	20.03	143.50	5/18/2021 10:53:11	19.11	143.08	5/24/2021 11:41:55	145:02:08
DS10	22.14	144.47	5/19/2021 10:09:51	22.49	144.36	5/23/2021 10:34:47	96:57:31
DS11	20.71	143.01	5/20/2021 19:47:17	20.88	142.99	5/23/2021 23:08:58	75:45:53
DS12	12.88	142.04	5/27/2021 19:39:07	12.94	141.76	5/29/2021 08:21:22	36:53:12
DS13	12.57	144.52	6/15/2021 11:26:47	11.67	142.89	6/24/2021 11:35:57	216:28:06
DS14	12.85	146.84	6/17/2021 11:04:46	14.48	141.88	7/11/2021 20:11:07	585:24:22
DS15	15.67	148.97	6/19/2021 12:30:20	15.61	149.21	6/21/2021 11:11:33	47:01:31
DS16	15.07	146.74	6/20/2021 09:59:11	15.05	146.74	6/26/2021 8:46:34	142:57:04
DS17	17.15	147.73	6/27/2021 09:53:15	18.07	148.05	7/08/2021 08:33:12	262:58:42
DS18	19.39	147.65	6/29/2021 05:03:29	19.55	148.78	7/07/2021 06:54:30	196:27:36
DS19	19.39	147.15	6/29/2021 12:01:39	19.76	148.22	7/07/2021 02:56:37	183:13:38
DS20	20.31	146.77	6/29/2021 19:46:49	20.59	148.52	7/06/2021 18:51:00	167:13:43
DS21	22.31	147.04	6/30/2021 15:16:53	22.15	146.59	7/03/2021 03:23:02	60:17:49
DS22	19.92	145.57	7/04/2021 02:32:48	19.98	145.73	7/05/2021 11:06:00	32:42:43

Appendix 2: Examining non-random sampling of DASBR drifts deployed in the Mariana Archipelago for beaked whale density estimation.

METHODS

Recorder deployment locations can be controlled and were selected without knowledge of beaked whale distribution in the study area. Initial recordings can therefore be considered random with respect to beaked whale density. However, with drifting recorders, it is possible that the oceanographic processes that affect drift could, over time, cause our recorders to be entrained in water masses with greater or lower than average beaked whale abundance. A rigorous test of this possibility is difficult, but we examine this by modeling beaked whale relative density over the duration of our recorder drifts. If beaked whale detection rates increase or decrease systematically over the course of our drifts, we should be concerned about non-random sampling.

We model beaked whale relative density as a smoothed function of elapsed time since deployment using a generalized additive model. Animal distributions tend to be clustered, so we do not assume that relative densities in adjacent recordings are independent in our model. We combine ten adjacent two-minute recordings and use the number of these ten recordings with acoustic detections (*#Detections*) as the dependent variable. To account for the expected clustering of acoustic detections (relative to a Poisson distribution) we model this acoustic detection rate as a function of elapsed time using a Tweedie distribution. We use the *gam* function in the *mgcv* package (citation) to fit the model:

$$\#Detections_{i,t} \sim \mu + f(ElapsedTime_t) + \varepsilon_{i,t},$$

where μ denotes an intercept term, the function *f* denotes a thin-plate spline fit, and ε denotes a Tweedie-distributed error term. For both species independently, this model was fit a) to separate drifts with 20 or more two-minute recordings with acoustic detections, b) to the pooled data from all drifts, and c) to the pooled data from all drifts in a given year (2018 and 2021). Because only two of 28 drifts were longer than 15 days, we limit our model to fitting to elapsed times of 15 days (360 hr) or less. The *mgcv* parameter *gamma* was set to 1.4 to avoid over-fitting, and the effective degrees of freedom for the spline fit was selected using generalized cross validation.

RESULTS

We modeled the number of two-minute recording with acoustic detections (out of ten adjacent recordings) as a function of elapsed time to evaluate whether the drifting recorders tended to drift into regions with either higher or lower than average densities of beaked whales. The results (Fig. Y) showed that, for all years and all drifts pooled, the detection probability is greatest at intermediate values of elapsed time for Cuvier's beaked whales and is lowest at intermediate values of elapsed time for Blainville's beaked whales. The elapsed-time term was a significant predictor of detection probability for both Cuvier's beaked whale (p = 0.004) and Blainville's beaked whale (p = 0.02) in the models with all drifts pooled. However, these results were not consistent among drifts or even between years (Fig. Y). Some drifts had higher detection rates at the beginnings, others at intermediate times, and others at the end of drifts. Beaked whale acoustic detections were extremely patchy, which limits our ability to make meaningful inferences about whether the drifting process could lead to non-random sampling of beaked whale habitats. Clearly, our result do not indicate monotonically increasing or decreasing detection probabilities over time, but a larger sample size would be needed to discern more subtle dependencies between detection probability and drift duration.

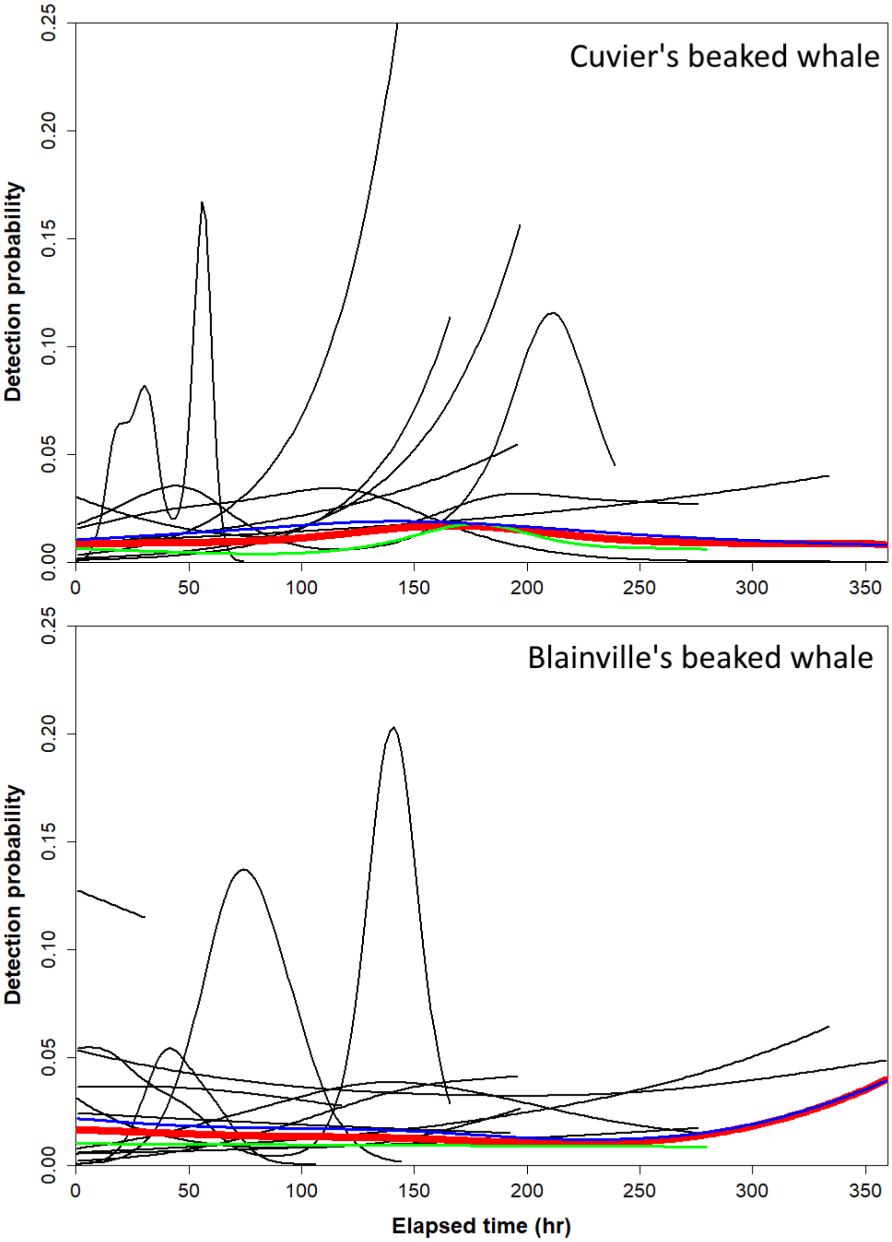

Figure Y. Modeled estimates of detection probability as a function of elapsed time since the drifting recorder was deployed. Models include all drifts pooled (red lines), 2018 drifts pooled (green lines), 2021 drifts pooled (blue lines), and for individual drifts with 20 or more recordings with acoustic detections. The model was fit to data from 10 adjacent files, but fitted values are re-scaled here to give the probability that a given two-minute recording will include a detection of a given species.

DISCUSSION

We did not detect monotonically increasing or decreasing patterns in average detection probabilities during the course of our drifts. However, we cannot rule out the possibility that the oceanographic processes that control drift could result in a biased sampling of beaked whale density for longer drifts or that a time-varying bias might be detectable with a larger sample size. The large variation in relative acoustic detection probability within our drifts tended to dominate the time-varying patterns we saw.

A more complicated approach to discerning potential biases resulting from the processes that control drift might be possible by examining changes in important habitat characteristics for beaked whales during the course of a drift. Instruments could be added to a drifting buoy recorder to measure variation in temperature, salinity and other oceanographic properties of the surface water over the course of a drift. Data from ocean circulation models could be combined with location information from drift tacks to estimate changes in deeper oceanographic parameters that might affect beaked whale distributions. However, to date, available oceanographic parameters (either measured or modeled) have added very little predictive power to models of beaked whale density (Fiedler et al. 2023). Even if oceanographic variables were found to change during the course of a drift, it is not at all certain that this could help explain variations in beaked whale density. Clearly beaked whale densities must depend upon their habitat, but at this point we are not able to measure the habitat variables that affect density.