Cuvier's Beaked Whale Behavioral Responses Persist After Conclusion of Some Navy Sonar Exposures

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Introduction:

- Cuvier's beaked whales (*Ziphius cavirostris*) respond to mid-frequency active sonar (MFAS) within the US Navy's Southern California Range Complex by ceasing foraging, increasing deep dive durations, and extending the period between presumed[3] deep foraging dives (commonly termed IDDIs).[1,2]
- We expand upon these results by quantifying post-exposure behavioral changes and identifying exposure characteristics that drive these responses.

Methods:

- 13 tags with 29 days of concurrent MFAS from 2011-2015 at SCORE.[2]
- Deep dive cycle (DDC): Start of deep, presumed foraging dive to end of IDDI
- DDCs were considered exposed if MFAS occurred within 100 km of the whale.[2]
- Mahalanobis distances (MDs) were calculated for each DDC using: deep dive duration and depth, total shallow dive and surface duration, and the number of shallow dives within each DDC.
- DDCs in early January, when exposures are traditionally absent, were used to calculate baseline distribution centers and the covariance matrix across whales
- MDs for unexposed DDCs within 6 days of the end of sonar were modeled using generalized additive models[4] to measure the extent to which DDCs varied from baseline behaviors over time following high- and mid-power exposures.
- Models included time of day, ocean basin, sex, a smooth term for days since sonar end, and tensor product interactions between the number of days since sonar ended and a combination of non-collinear covariates:
  - closest source distance or last source distance
  - duration of preceding sonar silence
  - total sonar duration, number of sonar bouts within exposure, or time span from start to end of exposure event

Ethics:

Field work was carried out under the US National Marine Fisheries Service permit numbers 540-1811 and 16111. Tags were deployed in accordance with the IACUC guidelines for satellite tagging established by Cascadia Research Collective.

References:

1. DeRuiter et al. (2013) First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology letters*.
2. Falcone et al. (2017) Diving behaviour of Cuvier's beaked whales exposed to two types of military sonar. *Royal Society Open Science*. Wood (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society*.
3. Sweeney et al. (2022) Cuvier's beaked whale foraging dives identified via machine learning using depth and triaxial acceleration. *Marine Ecology Progress Series*.
4. Wood (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society*.

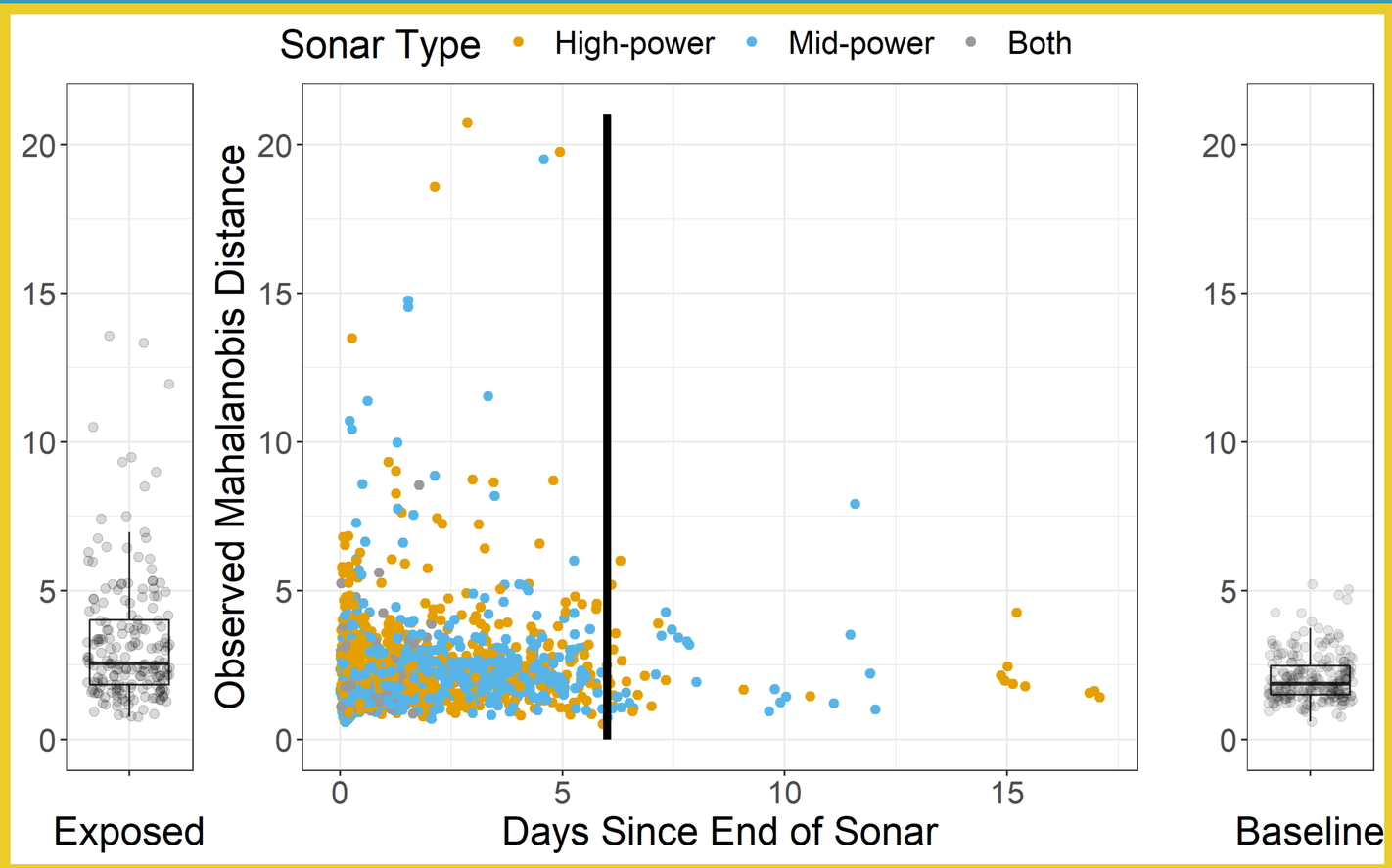
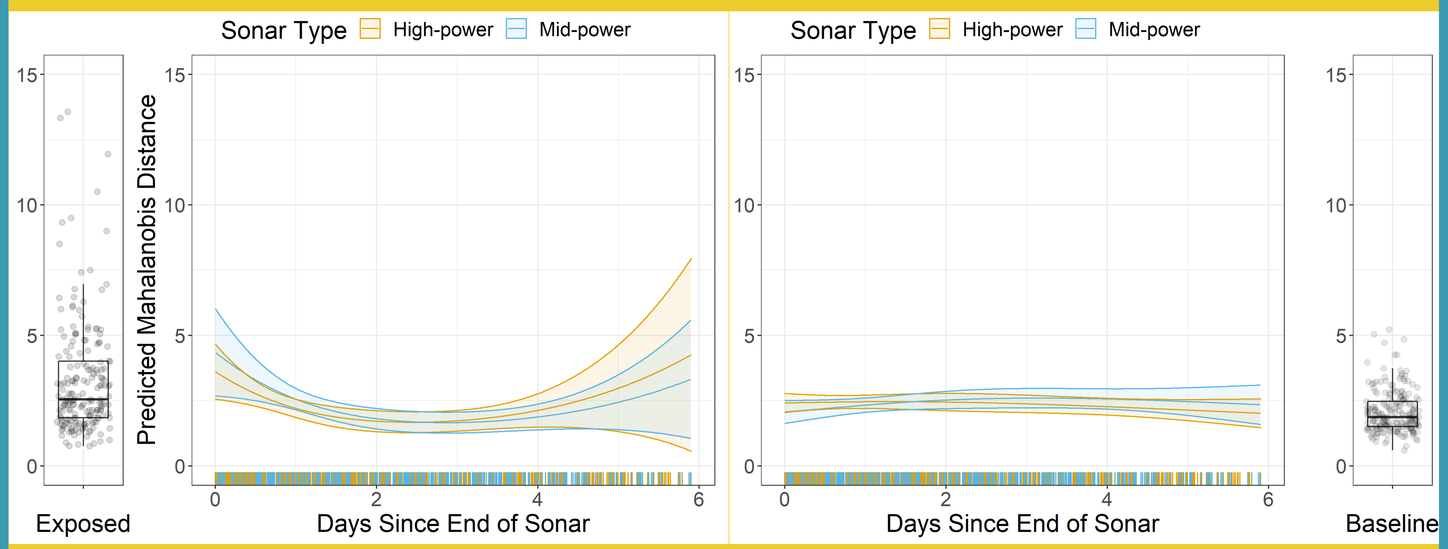


Figure 1. Observed Mahalanobis distances (MDs)

Center panel contains MDs from unexposed deep dive cycles (DDCs) following the conclusion of MFAS exposure events. The black line displays the 6-day cutoff after which data were excluded from modeling. The left and right panels show the distributions of MDs during exposed DDCs (left) and early-January baseline DDCs (right).

Cuvier's beaked whale behavioral responses can persist beyond conclusion of some MFAS exposures



Figures 2-3. Model prediction plot with fixed terms set as follows:

- time of day = night, ocean basin = San Nicolas, sex = female
- last source distance = 50 km (high) and 5 km (mid)
- days of preceding sonar silence = 3.5 (high) and 0.25 (mid)
- number of bouts = 4 (high) and 1 (mid)
- last source distance = 50 km (high) and 25 km (mid)
- days of preceding sonar silence = 3.5 (high) and 2 (mid)
- number of bouts = 1 (high) and 11 (mid)

Table 1. Observed data summary for variables used in the calculation of Mahalanobis distances for exposed, unexposed, and baseline deep dive cycles (DDCs).

	Exposed DDCs		Unexposed DDCs		Baseline DDCs	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Deep Dive Duration	68.9 (14.1)	39.9-163.3	64.5 (11.7)	27.1-114.7	63.7 (11.5)	36.8-100.2
Deep Dive Depth	1381.2 (263.9)	767.5-1999.5	1398.4 (270.3)	703.5-2991.5	1437.4 (256.4)	879.5-1871.5
Number of Shallow Dives	5.9 (3.4)	0-19	4.3 (2.3)	0-21	4.6 (2.1)	0-10
Total Shallow Dive Duration	144.7 (103.9)	0-609.6	87.1 (55.0)	0-568.0	90.7 (47.4)	0-266.4
Total Surface Duration	21.0 (18.8)	4.1-137.4	22.9 (25.6)	1.3-270.7	18.7 (12.9)	3.7-82.8

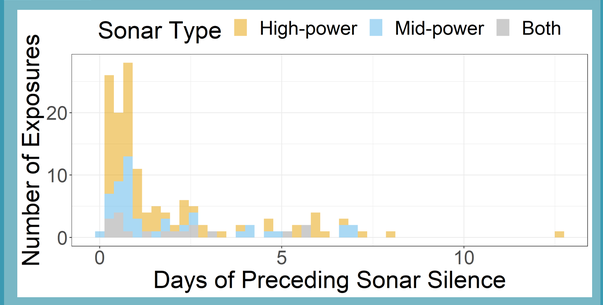
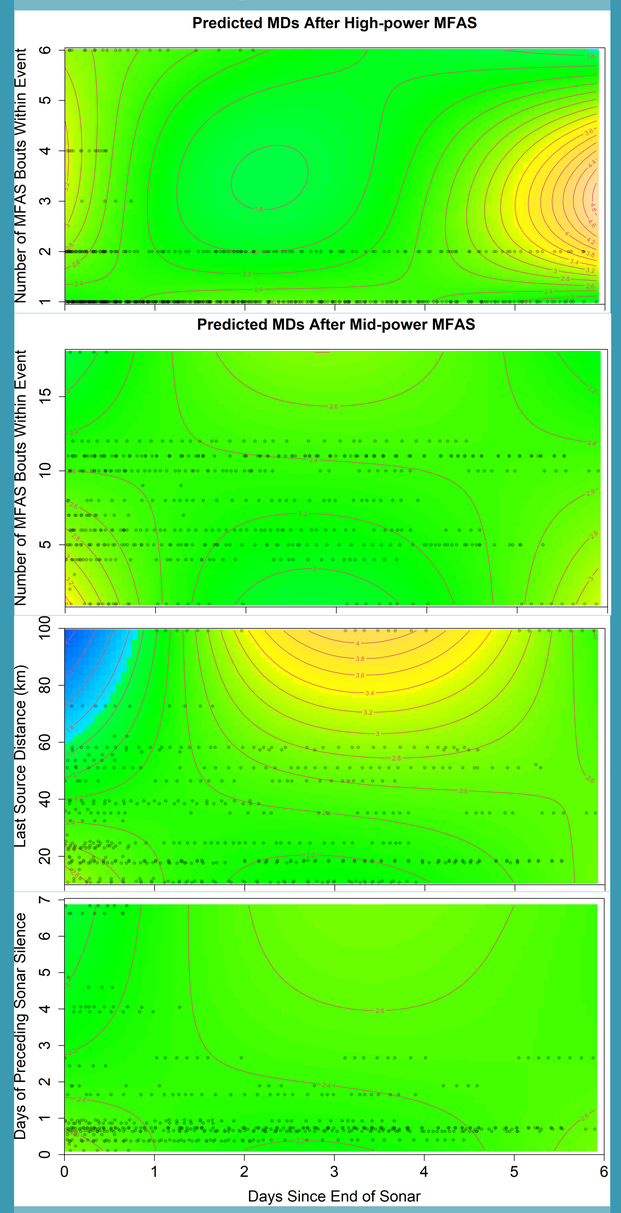
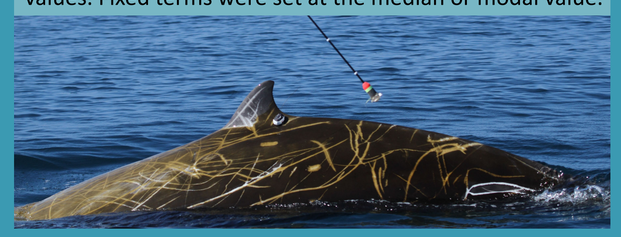


Figure 4. Histogram showing the durations of sonar silence preceding MFAS exposure events



Figures 5-8. Contour plots for predicted Mahalanobis distances (MDs) as a function of the statistically significant interactions between days since the end of sonar and sonar covariates. Black points show the distribution of observed values. Fixed terms were set at the median or modal value.