SUPPLEMENTARY INFORMATION

Assessing the role of sampling uncertainty when predicting behavioural responses of tagged cetaceans exposed to naval sonar

Phil J Bouchet[1,2], Catriona M Harris[1] and Len Thomas[1,2]

Front. Mar. Sci. | doi: 10.3389/fmars.2021.674554

Author affiliations

[1]Centre for Research into Ecological and Environmental Modelling (CREEM), University of St Andrews, St Andrews, UK
[2]School of Mathematics and Statistics, University of St Andrews, St Andrews, UK

Correspondence

Phil J Bouchet | pb282@st-andrews.ac.uk

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

This research was financially supported by the US Navy Living Marine Resources Programme (LMR) Contract No. N3943018C2080. We thank Rob Schick and the Atlantic BRS project for providing the Argos ellipse data. Support for the Atlantic BRS project is provided by Naval Facilities Engineering Command Atlantic under Contract No. N62470-15-D-8006, Task Order 18F4036, Issued to HDR, Inc.

Contents

1. Supplementary methods

A full description of the R code used to simulate and analyse behavioural responses is given in [1]. The report can be accessed from https://github.com/pjbouchet/brs_uncertainty/.

2. Supplementary figures

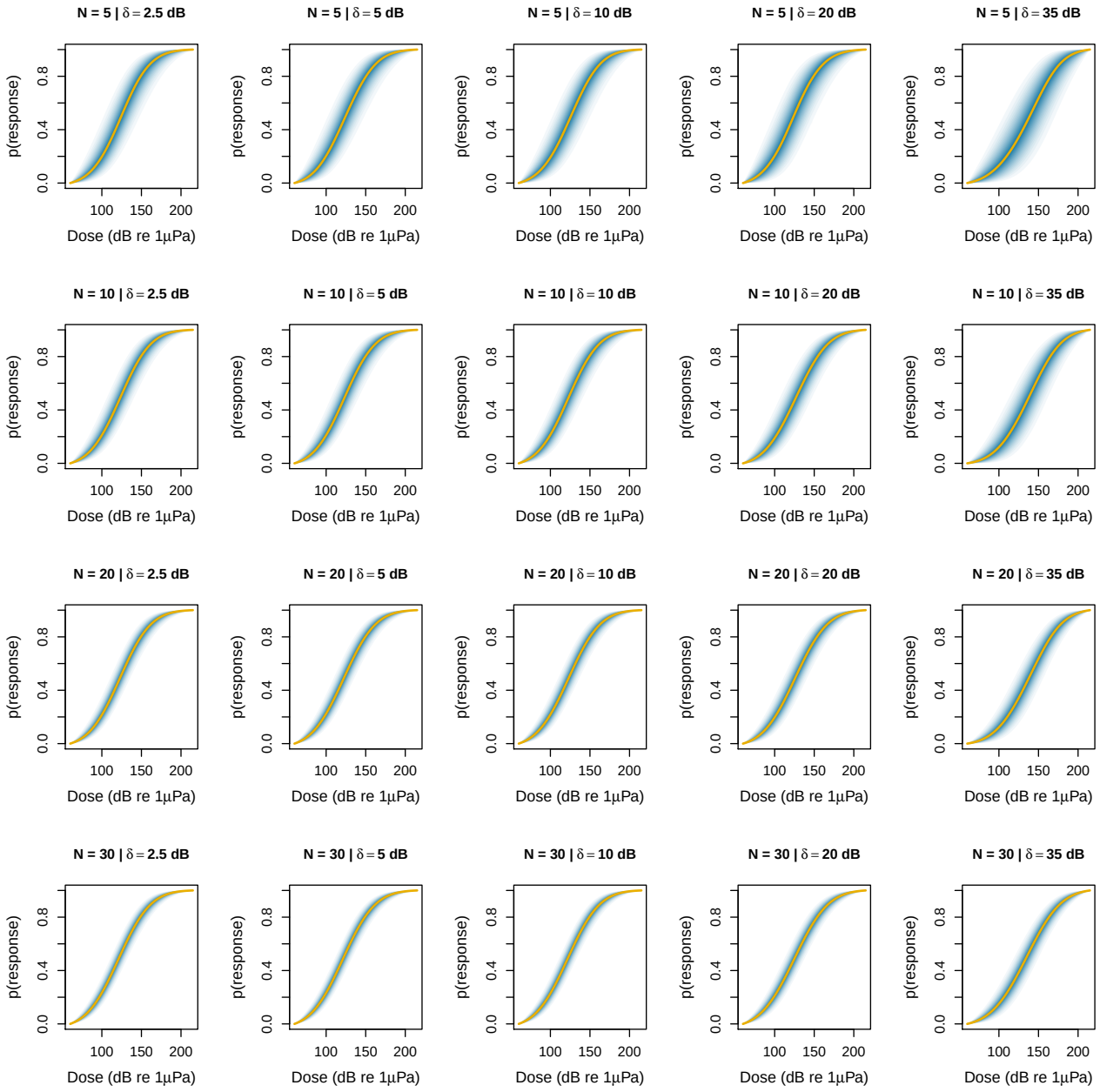

Figure S1: Dose-response curves estimated from the reduced Bayesian hierarchical model (single tag type), for a range of sample sizes (N) and sampling errors (δ). The solid line represents the average posterior median across Ns = 100 simulations, followed by the average 5%, 10%, 15% … and 95% credible intervals in darker to lighter shades of blue.

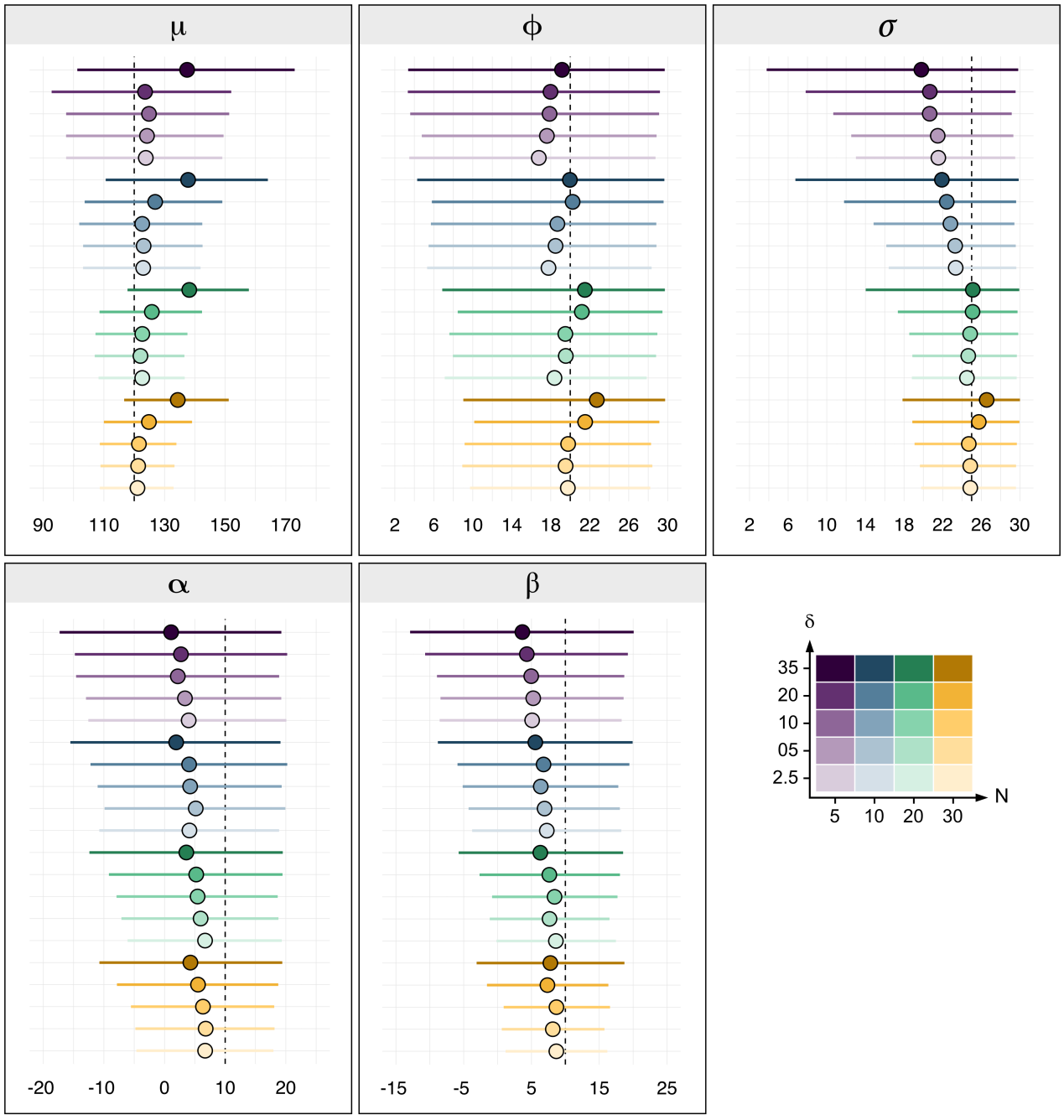

Figure S2: Posterior estimates of parameters from the reduced model, including the location parameter relating to the mean response threshold for all whales (μ), the scale parameters relating to the between-whale variation (ϕ) and the within-whale between-exposure variation (σ), and the two contextual covariates considered (exposure history, α, and sonar signal type, β). Circles and bars respectively denote the average posterior median and credible intervals across 100 simulations, for different combinations of sample sizes (N) and sampling errors (δ). X-axis scales are expressed in dB (re 1µPa). Dashed lines mark the true underlying values for each parameter.

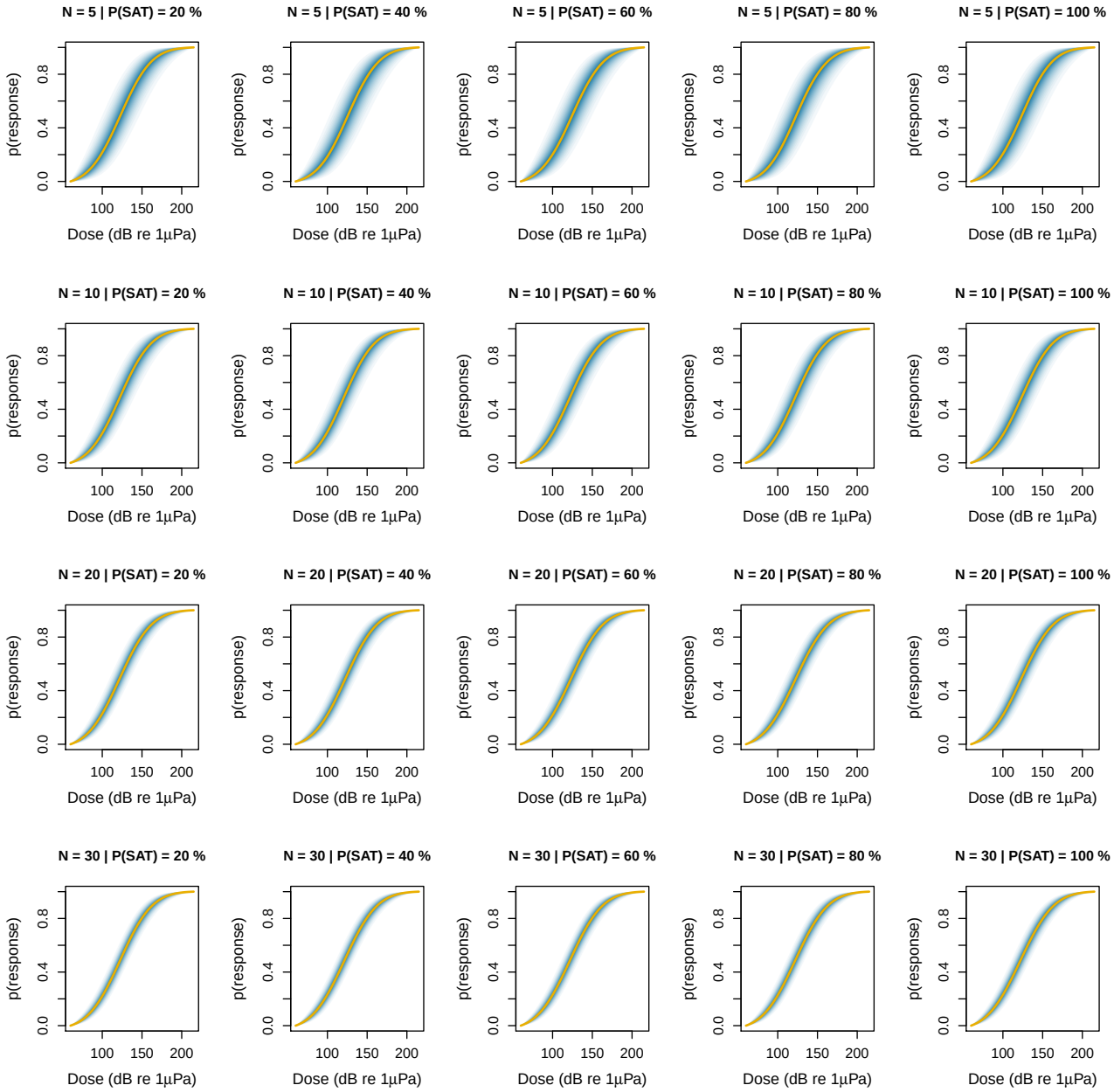

Figure S3: Dose-response curves estimated from the full Bayesian hierarchical model (multiple tag types, with varying errors), for a range of sample sizes (N) and proportions of animals carrying satellite tags ($P_{S\text{-}TAG}$). The solid line represents the average posterior median across Ns = 100 simulations, followed by the average 5%, 10%, 15% ... and 95% credible intervals in darker to lighter shades of blue.

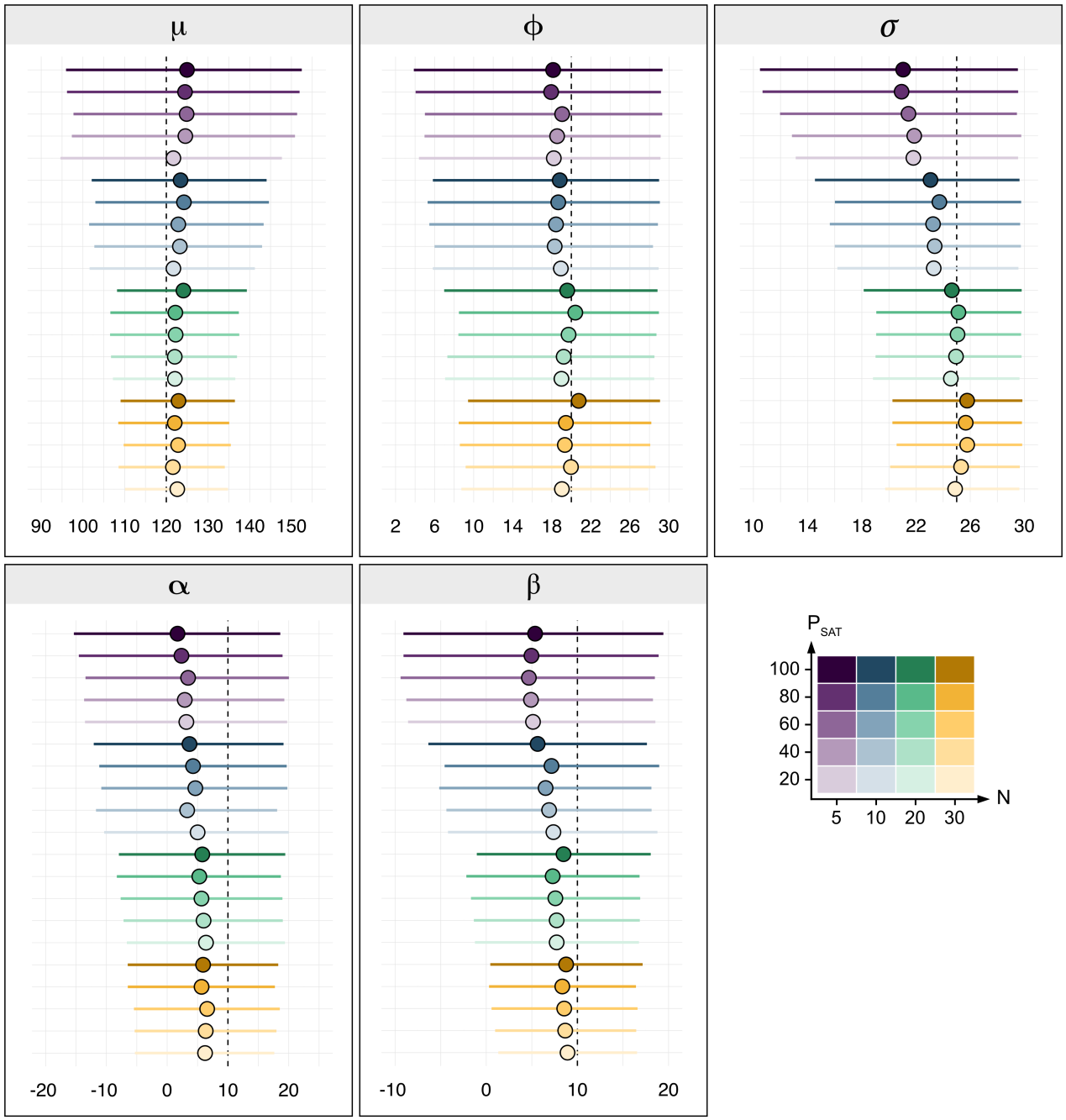

Figure S4: Posterior estimates of parameters from the full model, including the location parameter relating to the mean response threshold for all whales (μ), the scale parameters relating to the between-whale variation (ϕ) and the within-whale between-exposure variation (σ), and the two contextual covariates considered (exposure history, α, and sonar signal type, β). Circles and bars respectively denote the average posterior median and credible intervals across 100 simulations, for different combinations of sample sizes (N) and tag ratios (i.e., proportion of satellite tags, $P_{S\text{-}TAG}$, in %). X-axis scales are expressed in dB (re 1µPa). Dashed lines mark the true underlying values for each parameter.

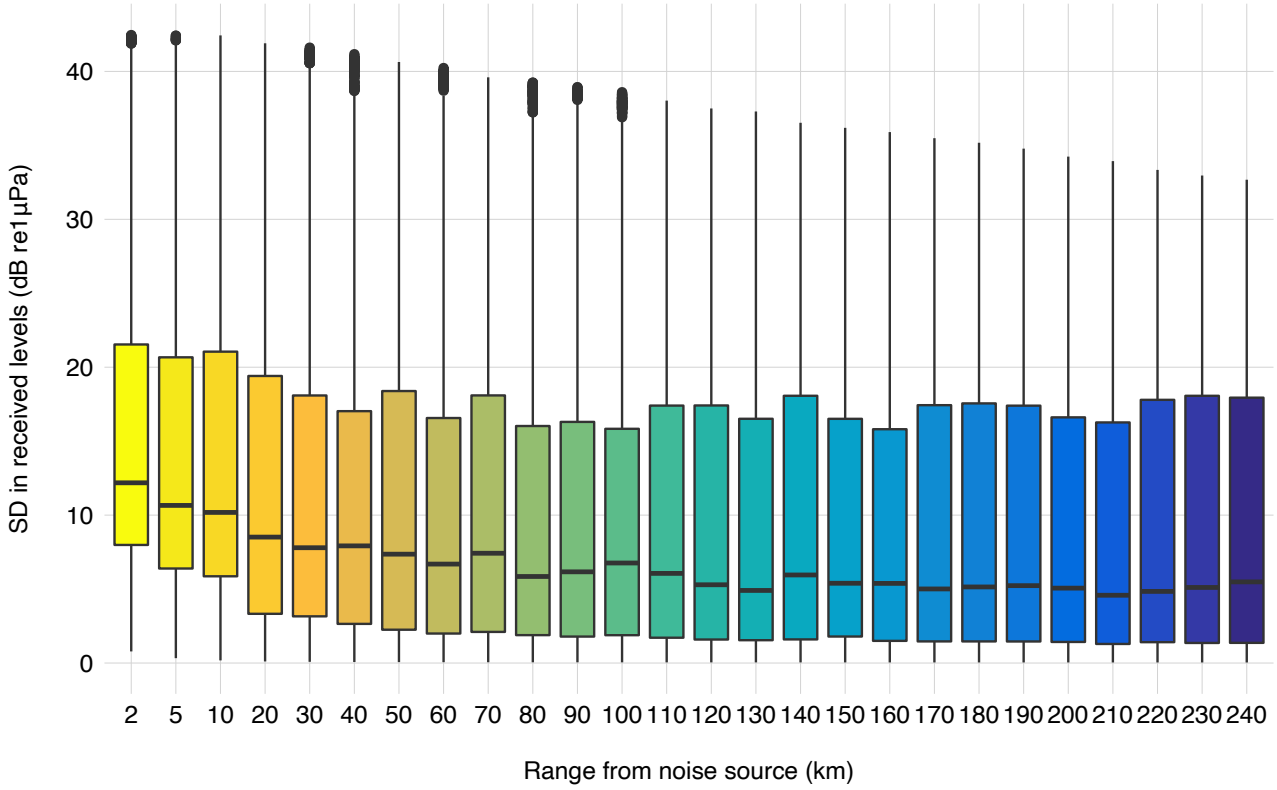

Figure S5: Variation in the uncertainty surrounding the estimated acoustic dose experienced by 1,000 simulated animals carrying Argos-linked satellite tags, at incremental distances from a sonar source (located at distance = 0). Values are expressed as the standard deviation (SD) in received levels across 10,000 candidate locations sampled within plausible error ellipses around each individual, assuming spherical loss of the acoustic signal (see main text for details).

3. Supplementary tables

Table S1: Summary of major controlled exposure experiments (CEEs) funded to date by the world's Navies (see [2] for a comprehensive review). N represents the number of tagged animals, as reported in the literature at the time of the study/ies listed in the Reference column. This excludes additional animals that may have been monitored through other means (e.g., passive acoustics, visual follows). AUTEC: Atlantic Undersea Testing and Evaluation Center. 3S:Sea Mammals, Sonar, Safety. SOCAL: Southern California. * Due to logistical difficulties and inclement weather conditions, no sonar exposures were actually conducted during MED-09.

Name	Location	Year(s)	Focal species	N	DTAG	S-TAG	Reference
AUTEC-BRS	Bahamas **(Atlantic)**	2007–2008	Blainville's beaked whales	8	✓	✓	[3]
MED-09*	Balearic Islands, Alboran Sea, Sardinia **(Mediterranean)**	2009	Cuvier's beaked whales, long-finned pilot whale	2	✓	✗	[4]
3S/3S[2]	Norway, Svalbard **(North Atlantic and Arctic)**	2006–2015	Killer, long-finned pilot, sperm, humpback, minke, and northern bottlenose whales	30	✓	✗	[5–8]
SOCAL-BRS	Southern California **(Eastern Central Pacific)**	2010–2015	Cuvier's beaked whales, Risso's dolphins, several large baleen whale species (e.g., blue whales)	34	✓	✗	[9, 10]
Atlantic-BRS	Cape Hatteras **(Northwestern Atlantic)**	2017-present	Cuvier's beaked and short-finned pilot whales	14	✓	✓	[11]

Table S2: Number of Markov Chain Monte Carlo (MCMC) iterations discarded as burn-in under the reduced and full models. δ: Uncertainty in measurements of the acoustic dose in the reduced model, expressed as a standard deviation (SD, in dB). P(S-TAG): Proportion of animals carrying satellite tags in the full model (in %).

δ	P(S-TAG)	Burn-in
2.5	20	25,000
5	40	25,000
10	60	50,000
20	80	75,000
30	100	100,000

References

1. Bouchet, P. J., Harris, C. & Thomas, L. (2020). Simulating cetacean responses to sonar exposure within a Bayesian hierarchical modelling framework - R code description. Double MOCHA Report, University of St Andrews, 20 p.
2. Southall, B. L., Nowacek, D. P., Miller, P. J. O. & Tyack, P. L. (2016). Experimental field studies to measure behavioral responses of cetaceans to sonar. Endangered Species Research **31**, 293–315. DOI: 10.3354/esr00764.
3. Tyack, P. L. *et al.* (2011). Beaked whales respond to simulated and actual Navy sonar. PLoS One **6**, e17009. DOI: 10.1371/journal.pone.0017009.
4. D'Amico, A., Southall, B. & Tyack, P. (2009). MED-09 final cruise report. SSC Pacific Technical Document 3243, 96 p. Available at: https://apps.dtic.mil/sti/pdfs/ADA533450.pdf.
5. Miller, P. *et al.* (2011). The 3s experiments: Studying the behavioural effects of naval sonar on killer whales (orcinus orca), sperm whales (physeter macrocephalus), and long-finned pilot whales (globicephala melas) in norwegian waters. SOI Technical Report SOI-2011-001, 290 p. Available at: https://bit.ly/3S_experiments.
6. Miller, P. J. *et al.* (2012). The severity of behavioral changes observed during experimental exposures of killer (orcinus orca), long-finned pilot (globicephala melas), and sperm (physeter macrocephalus) whales to naval sonar. Aquatic Mammals **38**. DOI: 10.1578/AM.38.4.2012.362.
7. Kvadsheim, P. *et al.* (2012). Behavioural responses of cetaceans to naval sonar signals in norwegian waters – the 3S-2012 cruise report. Norwegian Defence Research Establishment (FFI), 105 p. Available at: http://rapporter.ffi.no/rapporter/2012/02058.pdf.
8. Lam, F.-P. A. *et al.* (2016). Controlled Sonar Exposure Experiments on Cetaceans in Norwegian Waters: Overview of the 3S-Project. *In: The Effects of Noise on Aquatic Life II*, pp. 589–598, Springer, New York, NY.
9. Southall, B. L. *et al.* (2012). Marine mammal behavioral response studies in southern california: advances in technology and experimental methods. Marine Technology Society Journal **46**, 48–59. DOI: 10.4031/MTSJ.46.4.1.
10. Southall, B. L. *et al.* (2019). Behavioral responses of individual blue whales (*Balaenoptera musculus*) to mid-frequency military sonar. Journal of Experimental Biology **222**, jeb190637. DOI: 10.1242/jeb.190637.
11. Schick, R. S. *et al.* (2019). Accounting for positional uncertainty when modeling received levels for tagged cetaceans exposed to sonar. Aquatic Mammals **45**, 675–690. DOI: 10.1578/AM.45.6.2019.675.