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Supporting Information: Jones-Todd, C. M., E. Pirotta, J. W. Durban, D. E. Claridge, R. W. Baird, E. A. Falcone, G. S. Schorr, S. Watwood, and L. Thomas. Discrete-space continuous-time models of marine mammal exposure to Navy sonar. *Ecological Applications.*

Appendix S2. Additional case studies: Southern California Range Complex and Hawaii Range Complex

In addition to Blainville's beaked whale data collected at AUTEC, we applied our analytical approach to data from four cetacean species with different movement behavior and ecology, occurring over two other U.S. Navy ranges, the Hawaii Range Complex (HRC) and the Southern California Range Complex (SOCAL) (Figs S1, S4, S7, and S10). For these data, preliminary analysis showed that there were individuals with fewer than 50 observations whose tracks never left the range (i.e., for which transition rates could not be estimated); hence we used this threshold to exclude those tracks from further analyses.

Appendix S2: Data

In SOCAL, satellite telemetry data were available for two cetacean species: Cuvier's beaked whales (*Ziphius cavirostris*; $n = 12$) and fin whales (*Balaenoptera physalus*; $n = 39$). Cuvier's beaked whales were tagged with Wildlife Computers SPLASH10 transmitters in the Low Impact Minimally Percutaneous External-electronics Transmitter (LIMPET; Wildlife Computers, Redmond, WA, USA) configuration, using a Dan-Inject pneumatic projector (Børkop, Denmark). Three types of tags were used for fin whales: Wildlife Computers SPOT5 tags ($n = 28$), Mk10A-A tags ($n = 10$), and SPLASH10-F tags ($n = 1$). Mean transmission duration was 51 days (range: 11-88) for Cuvier's beaked whales, and 44 days (range: 7-238) for fin whales. Location estimates of tagged whales were provided by the Argos system based on the least-squares estimation method. Data collection techniques are described in detail in Falcone et al. (2017) and Scales et al. (2017). Information on the use of mid-frequency active sonars (MFAS) in SOCAL was available from two sources: passive acoustic detections from the hydrophones in the Southern California Anti-submarine Warfare Range (SOAR) and records in the U.S. Navy's internal Sonar Positional Reporting System (SPORTS) database. The location and duration of each sonar exercise were compiled. More details on sonar data processing are available in Falcone et al. (2017).

In HRC, we considered telemetry data for two species: rough-toothed dolphins (*Steno bredanensis*; $n = 15$) and short-finned pilot whales (*Globicephala macrorhynchus*; $n = 24$). The tags were either SPOT5 or Wildlife Computers Mk10A tags in the LIMPET configuration, Argos-linked, and deployed following a similar protocol to the one used in SOCAL. Mean transmission duration was 14 days (range: 7-27) for rough-toothed dolphins, and 29 days (range: 4-89) for short-finned pilot whales. Further details of the data collection can be found in Baird et al. (2019); Baird (2016). Information on the use of MFAS in HRC was only available from the U.S. Navy's SPORTS database.

In both study areas, military operations occur over a diffuse region that does not match any of the available boundaries for the two Navy ranges. This is in contrast with AUTEC, where most operations occur within the boundaries of the instrumented range. We used information on the locations of sonar exercises to define the effective boundaries of the areas where animals were susceptible to being exposed to sonar (broadly referred to as 'ranges'). Particularly, we extracted the 50% and 95% contours of the bi-dimensional kernel density of the locations of known sonar exercises. The 50% contour was taken to represent the area where exercises occur more regularly, while the 95% contour, surrounded by a 100-km-wide buffer region (Falcone et al., 2017), was used as a more realistic representation of the entire area where exposure can occur. Analyses for each species were then repeated assuming each of the two area boundaries.

From the estimated tracks, we show that beaked whales and rough-toothed dolphins were more resident on their respective ranges (Figs S1 & S10 and Tables S1 & S2), in comparison to fin and pilot whales (Figs S4 & S7 and Tables S1 & S2). Calculated transition probabilities for each species are reported in Table S3; these are averaged across all animals that made each particular transition at least once. Rough-toothed dolphins did not leave the 95% HRC range; therefore, we did not model these data in relation to the larger HRC range.

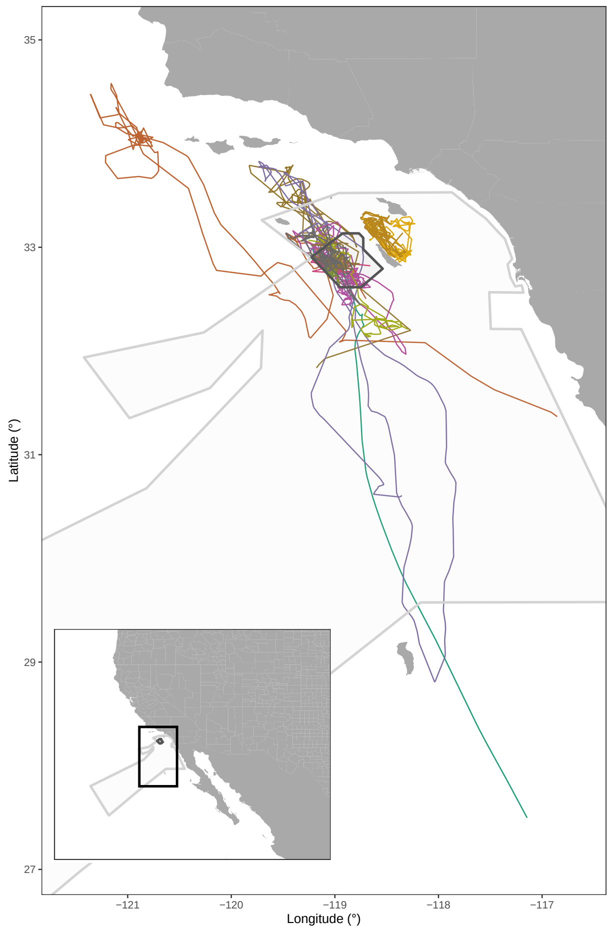

Figure S1: Estimated Cuvier's beaked whale tracks plotted over the boundaries of the Southern California Anti-Submarine Warfare Range (SOAR) (dark grey) and the Southern California Range Complex (light grey), which encompasses the area of authorized MFA sonar use. In comparison to fin whales (Fig. S4), this species remains in the range area; this is also evident in Table S1, where Cuvier's beaked whales are rarely seen outside the 95% range.

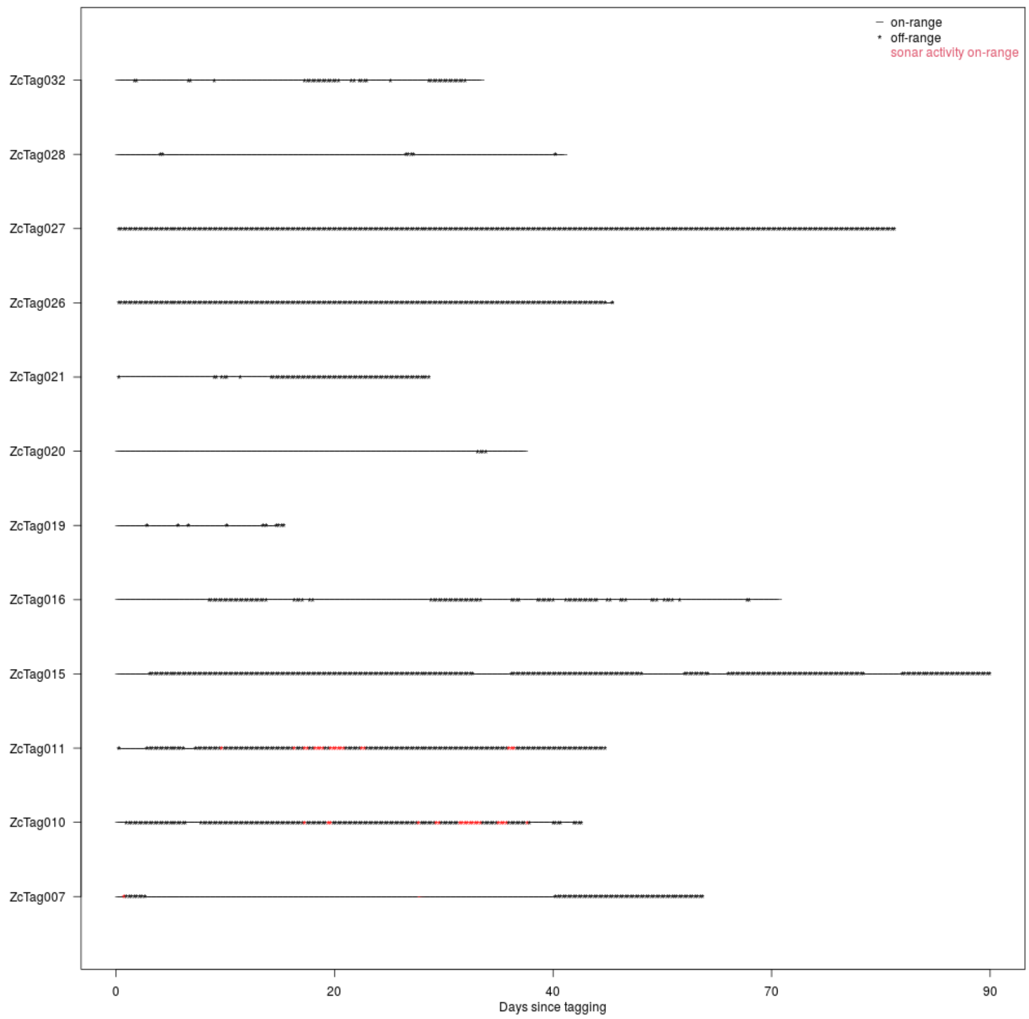

Figure S2: Plot showing the transitions and sonar exposure of Cuvier's beaked whales on the 50% SCORE range.

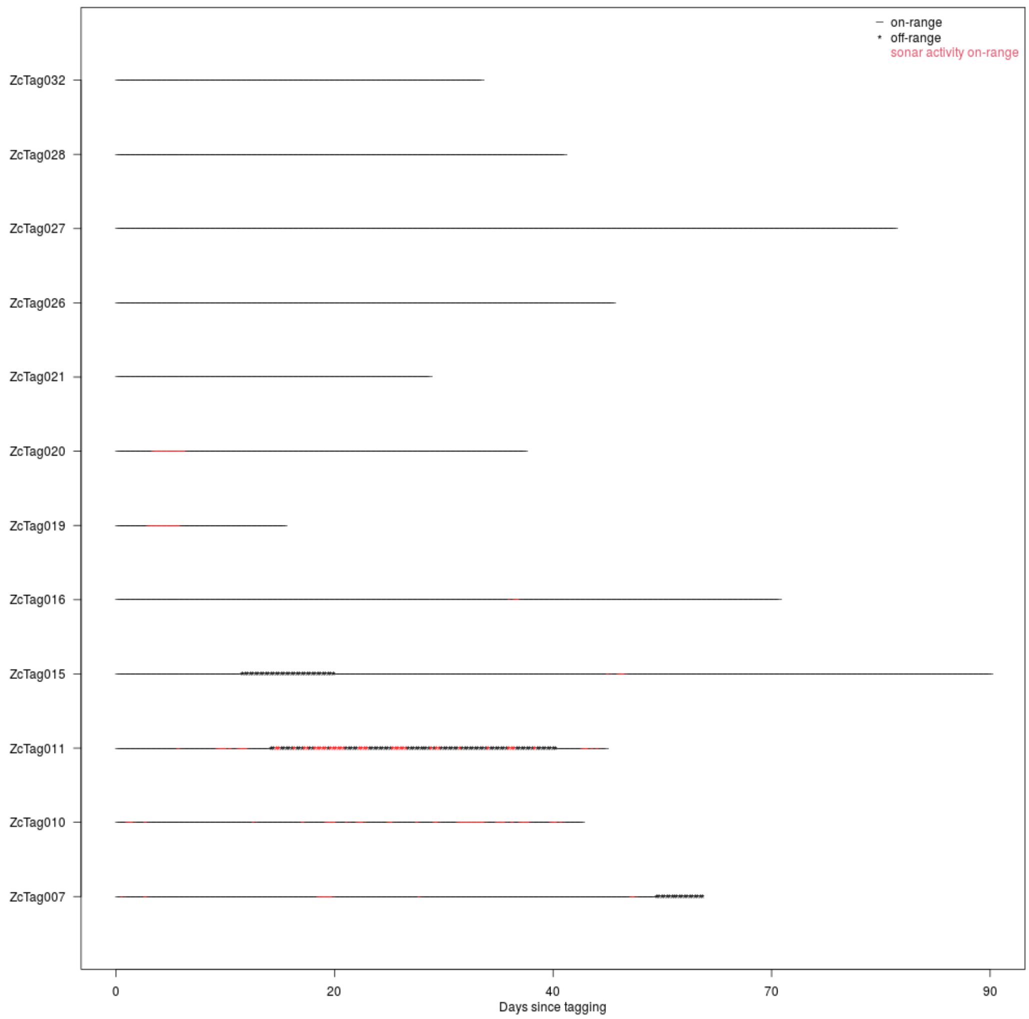

Figure S3: Plot showing the transitions and sonar exposure of Cuvier's beaked whales on the 95% SCORE range.

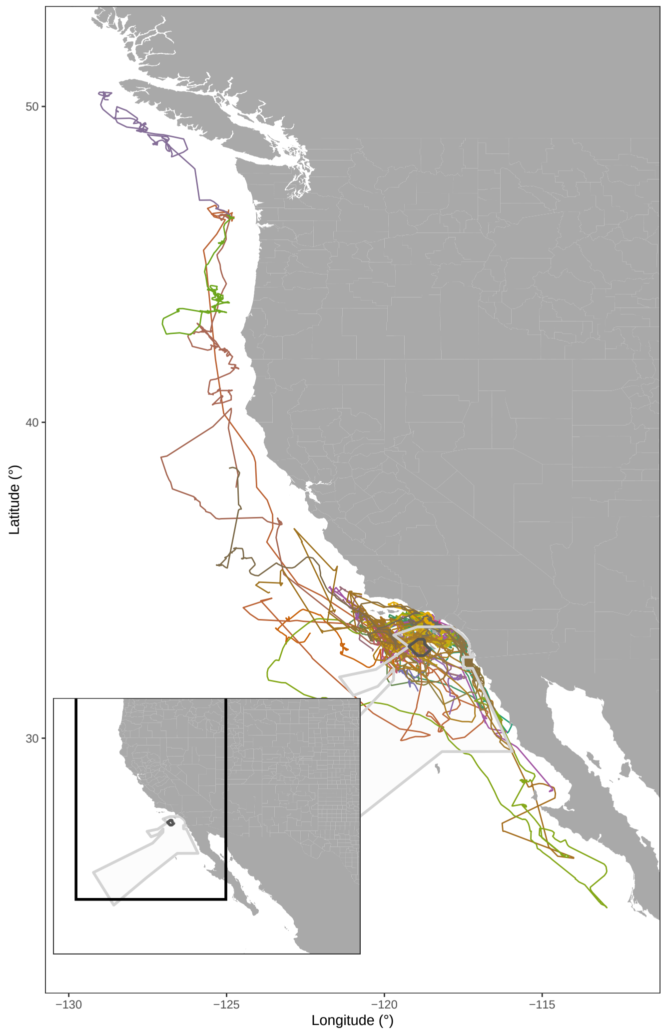

Figure S4: Estimated fin whale tracks plotted over the boundaries of the Southern California Anti-Submarine Warfare Range (SOAR) (dark grey) and the Southern California Range Complex (light grey), which encompasses the area of authorized MFA sonar use. In comparison to Cuvier's beaked whales (Fig. S1), this species travels further afield; this is also evident in Table S1, where fin whales are often observed outside the 95% range.

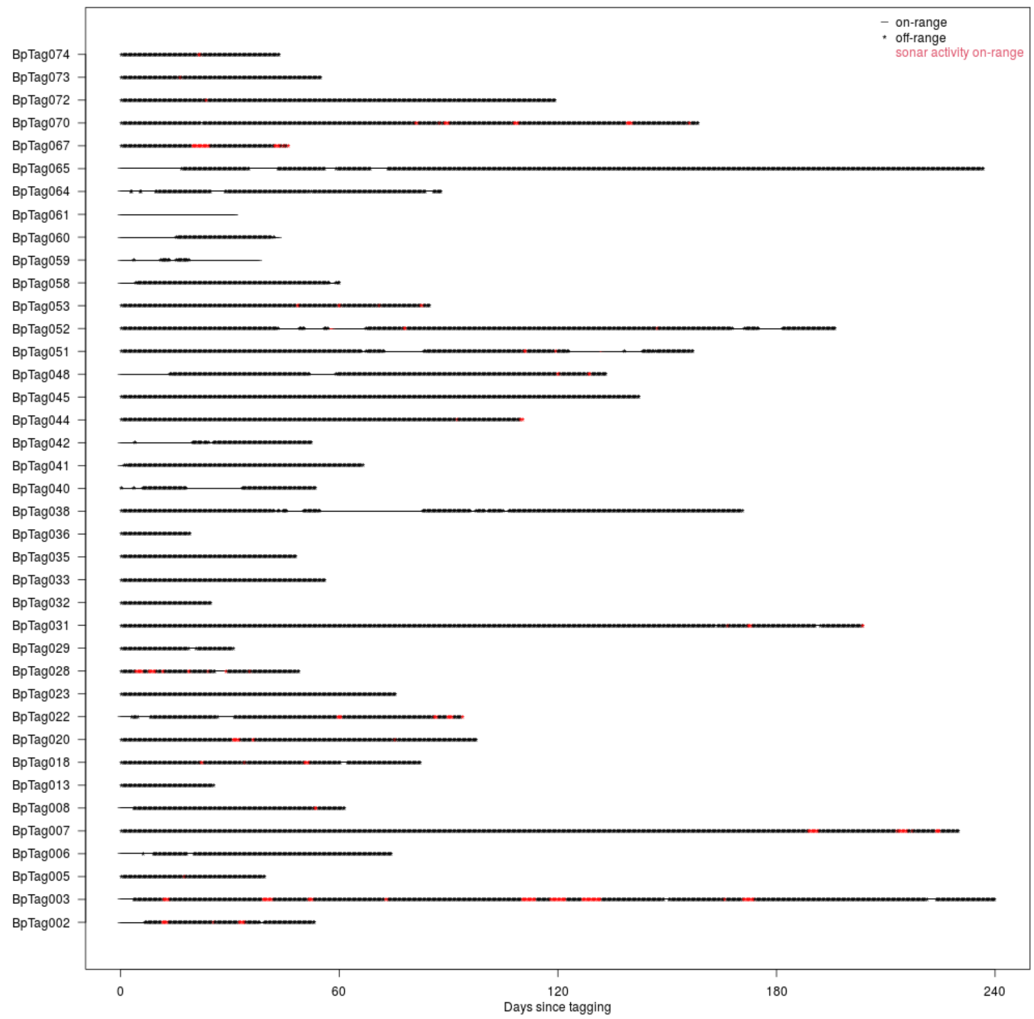

Figure S5: Plot showing the transitions and sonar exposure of fin whales on the 50% SCORE range.

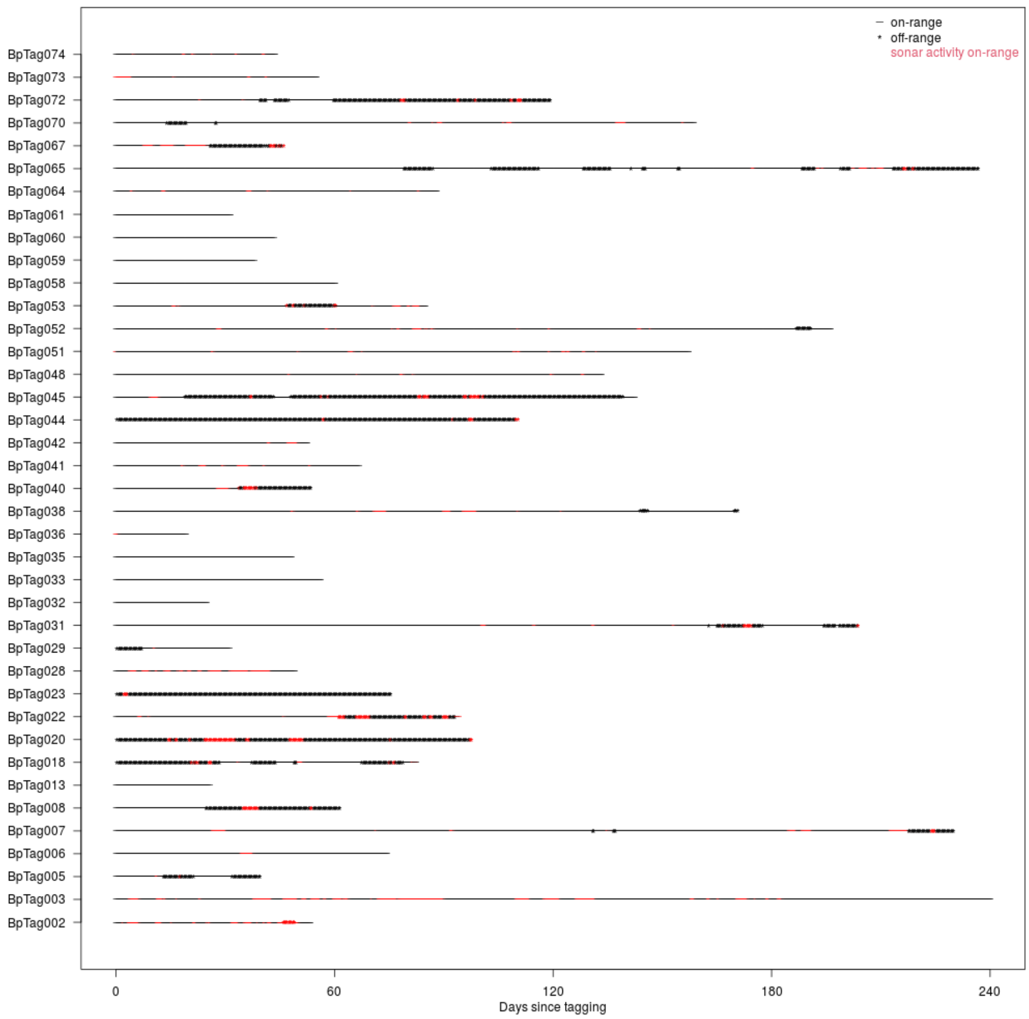

Figure S6: Plot showing the transitions and sonar exposure of fin whales on the 95% SCORE range.

		95% range		50% range	
Species	Individual ID	off-range	on-range	off-range	on-range
Cuvier's beaked whales	ZcTag007	19	208	67	160
	ZcTag010	0	180	160	20
	ZcTag011	111	78	175	14
	ZcTag015	36	302	275	63
	ZcTag016	0	256	88	168
	ZcTag019	0	65	10	55
	ZcTag020	0	158	4	154
	ZcTag021	0	121	69	52
	ZcTag026	0	192	190	2
	ZcTag027	0	301	301	0
	ZcTag028	0	173	7	166
	ZcTag032	0	141	41	100
Fin whales	BpTag002	9	139	127	21
	BpTag003	0	668	649	19
	BpTag005	46	64	110	0
	BpTag006	0	207	180	27
	BpTag007	40	600	640	0
	BpTag008	103	68	162	9
	BpTag013	0	71	71	0
	BpTag018	133	96	225	4
	BpTag020	272	0	272	0
	BpTag022	90	171	232	29
	BpTag023	210	0	210	0
	BpTag028	0	136	128	8
	BpTag029	20	66	81	5
	BpTag031	62	505	563	4
	BpTag032	0	69	69	0
	BpTag033	0	156	156	0
	BpTag035	0	134	134	0
	BpTag036	0	53	53	0
	BpTag038	9	466	371	104
	BpTag040	56	93	93	56
	BpTag041	0	185	182	3
	BpTag042	0	146	89	57
	BpTag044	307	0	307	0
	BpTag045	322	74	396	0
	BpTag048	0	371	314	57
	BpTag051	0	437	347	90
	BpTag052	12	534	459	87
	BpTag053	38	198	236	0
	BpTag058	0	167	151	16
	BpTag059	0	105	18	87
	BpTag060	0	120	74	46
	BpTag061	0	87	0	87
	BpTag064	0	245	207	38
	BpTag065	175	484	572	87
	BpTag067	56	72	128	0
	BpTag070	18	423	440	1
	BpTag072	185	147	332	0
	BpTag073	0	153	153	0
	BpTag074	0	121	121	0

Table S1: Number of observations on- and off-range (SOCAL) for each tagged fin and Cuvier's beaked whale, see Figs S1 and S4.

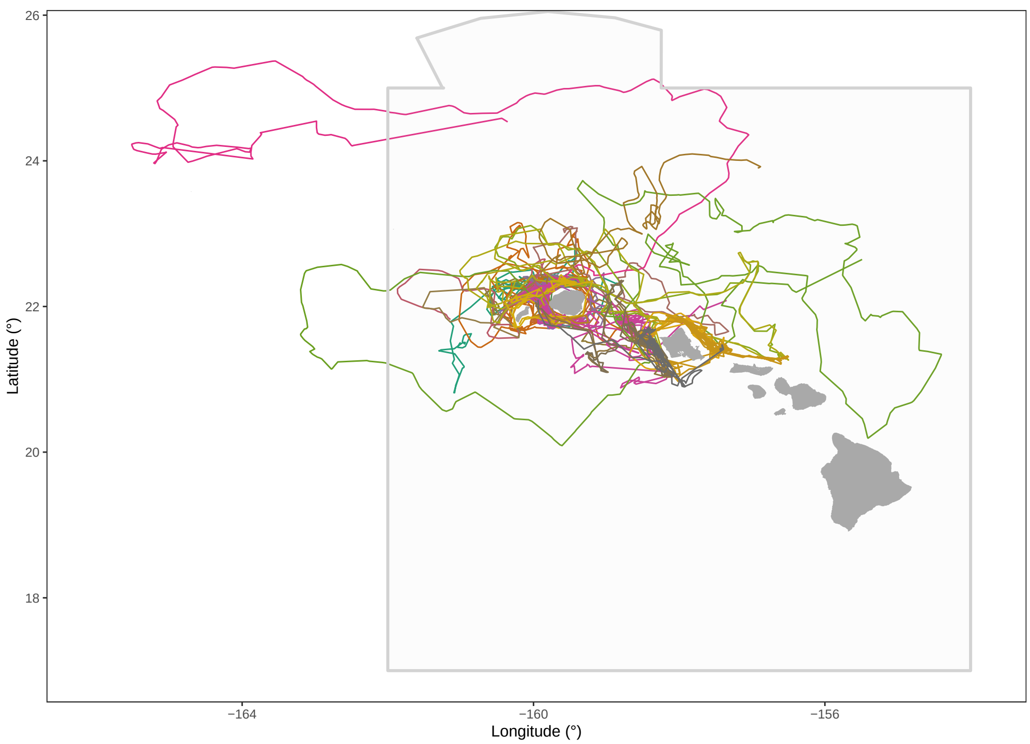

Figure S7: Estimated short-finned pilot whale tracks plotted over the boundaries of Hawaii Military Operating Area (light grey). In comparison to rough-toothed dolphins (Fig. S10), this species travels further from the range; this is also evident in Table S2.

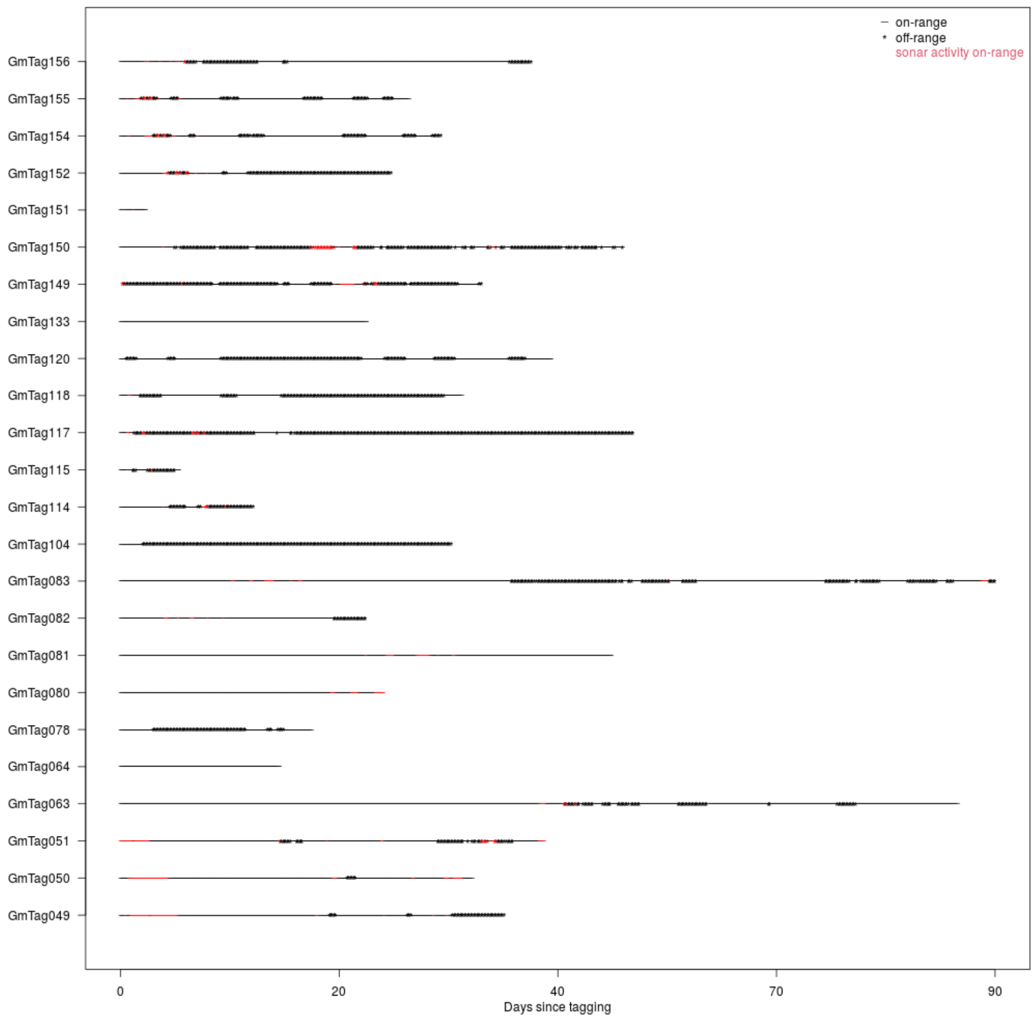

Figure S8: Plot showing the transitions and sonar exposure of short-finned pilot whales on the 50% PMRF range.

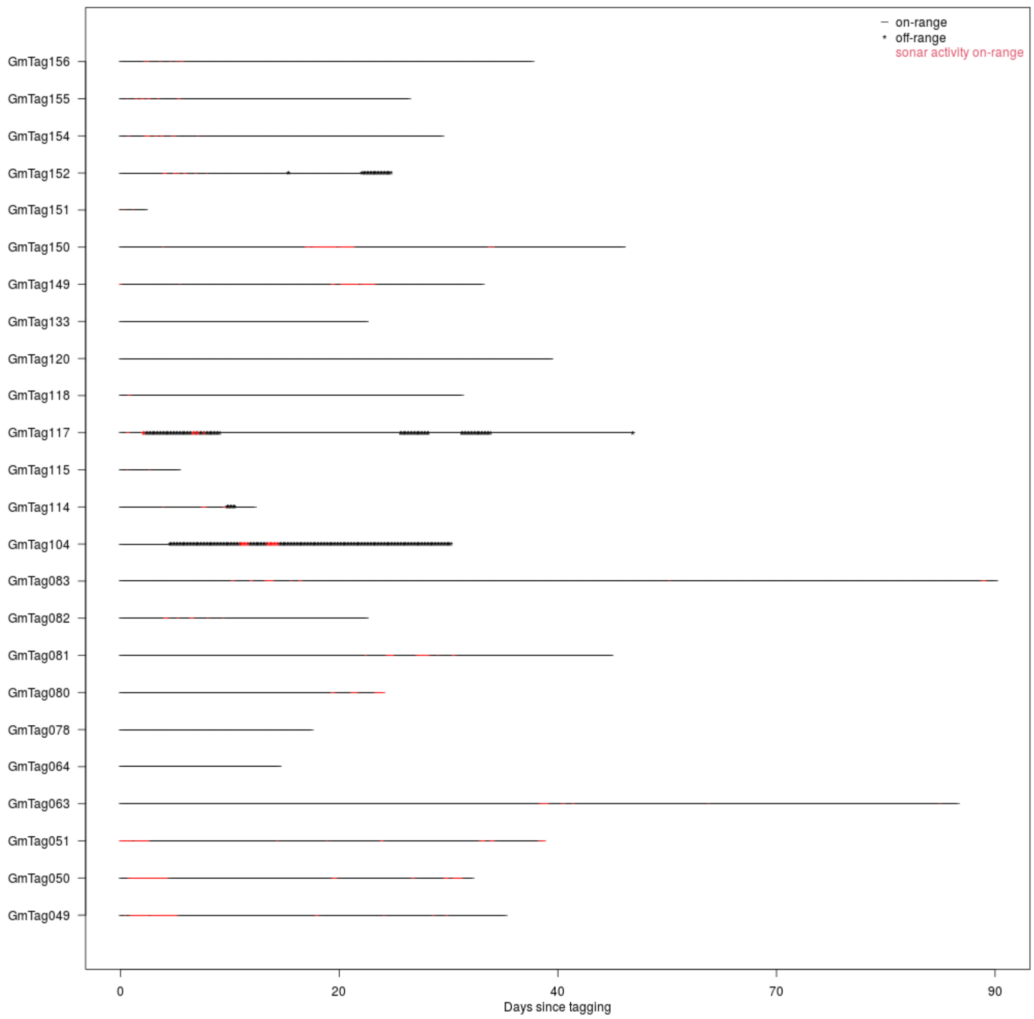

Figure S9: Plot showing the transitions and sonar exposure of short-finned pilot whales on the 95% PMRF range.

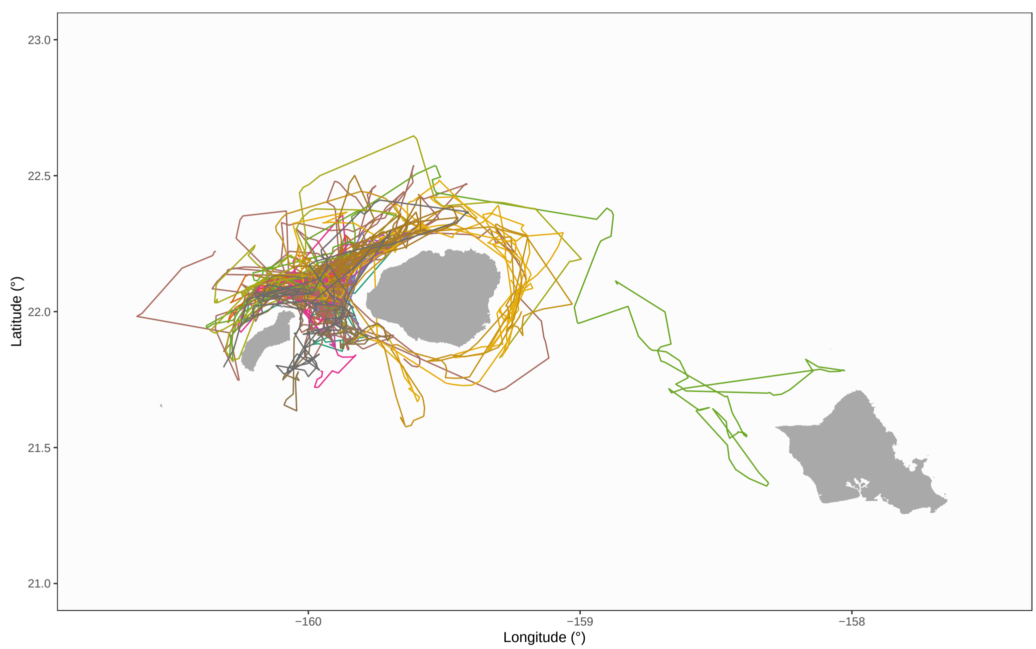

Figure S10: Estimated rough-toothed dolphin tracks. In comparison to short-finned pilot whales (Fig. S7), this species remained inside the Operating Area (see Table S1).

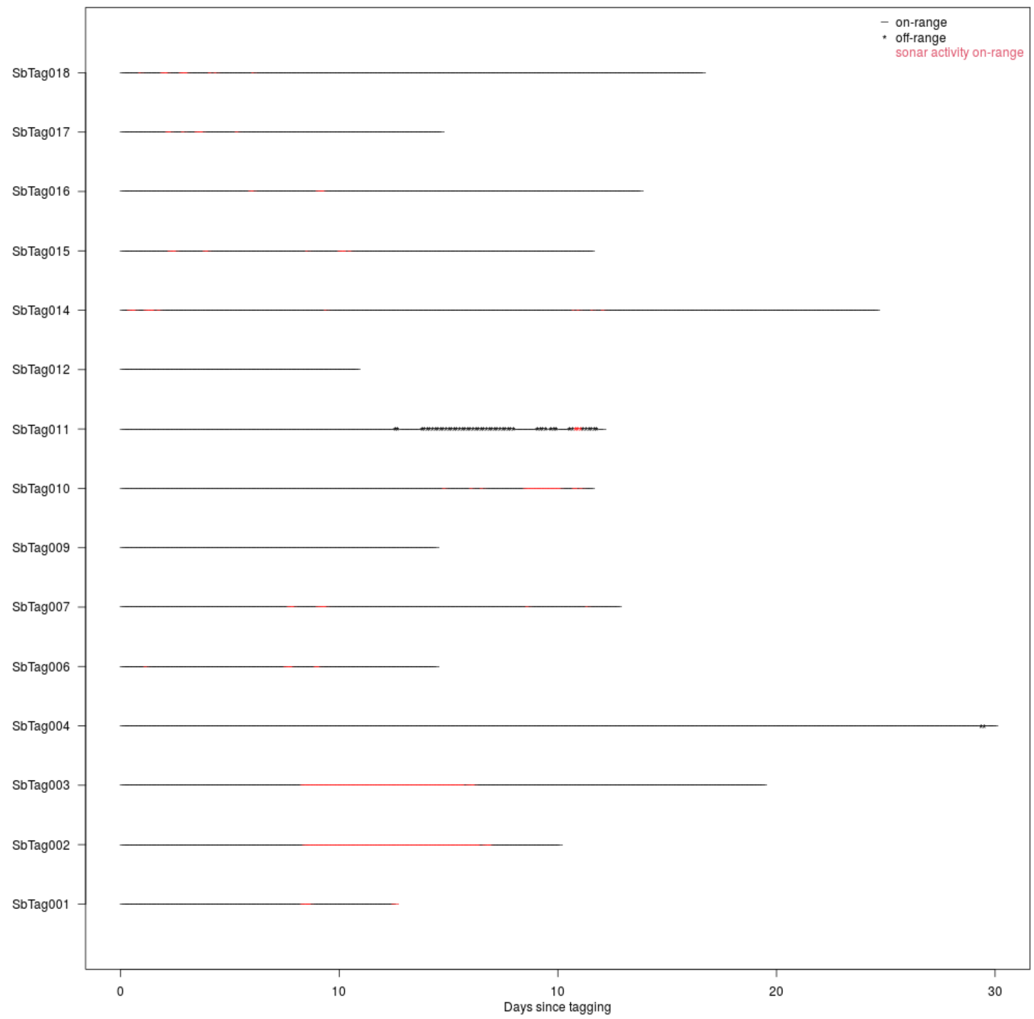

Figure S11: Plot showing the transitions and sonar exposure of rough-toothed dolphins on the 50% PMRF range.

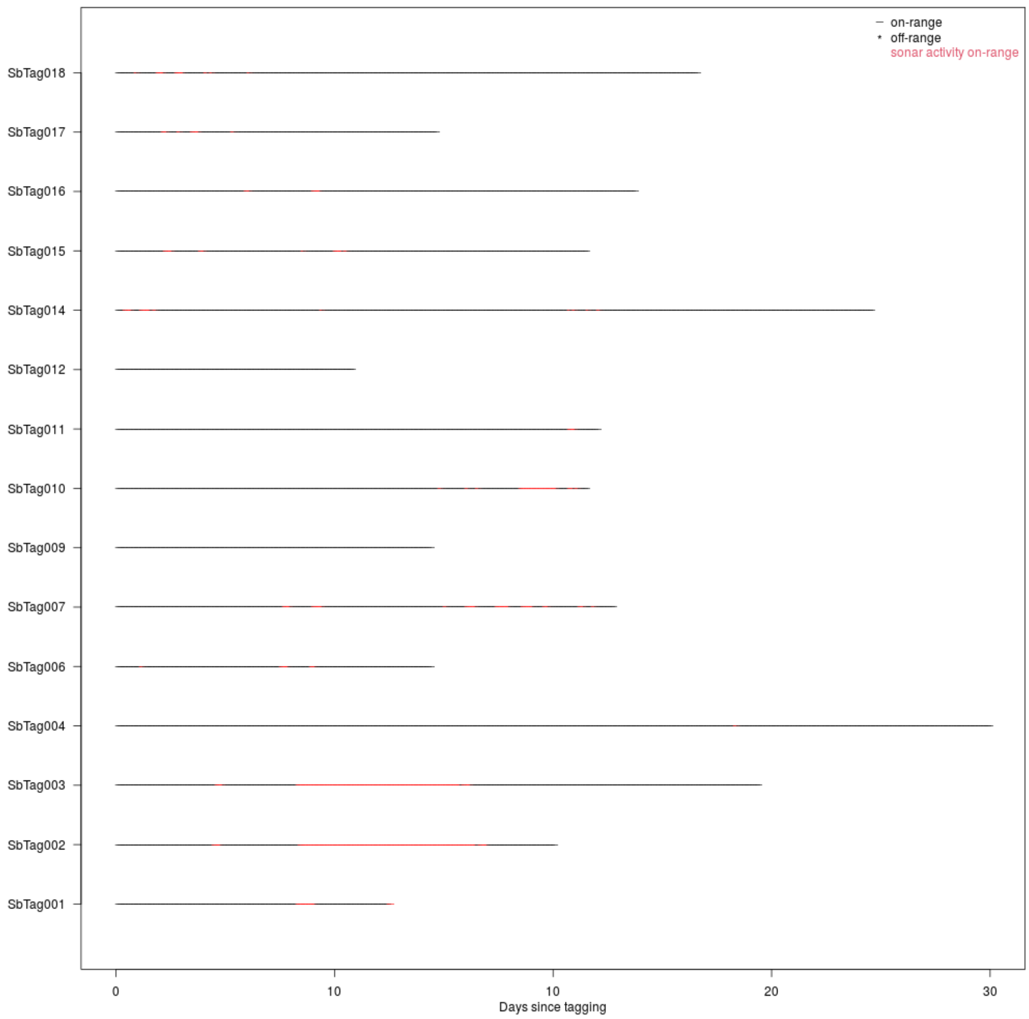

Figure S12: Plot showing the transitions and sonar exposure of rough-toothed dolphins on the 95% PMRF range.

		95% range		50% range	
Species	Individual ID	off-range	on-range	off-range	on-range
Short-finned pilot whales	GmTag049	0	255	43	212
	GmTag050	0	233	6	227
	GmTag051	0	281	54	227
	GmTag063	0	556	73	483
	GmTag064	0	105	0	105
	GmTag078	0	126	69	57
	GmTag080	0	174	0	174
	GmTag081	0	326	0	326
	GmTag082	0	163	22	141
	GmTag083	0	582	166	416
	GmTag104	188	32	206	14
	GmTag114	6	82	45	43
	GmTag115	0	38	22	16
	GmTag117	93	248	310	31
	GmTag118	0	226	135	91
	GmTag120	0	286	145	141
	GmTag133	0	163	0	163
	GmTag149	0	240	179	61
	GmTag150	0	334	226	108
	GmTag151	0	16	0	16
	GmTag152	21	159	113	67
	GmTag154	0	213	63	150
	GmTag155	0	191	57	134
	GmTag156	0	273	64	209
Rough-toothed dolphins	SbTag001	0	102	0	102
	SbTag002	0	163	0	163
	SbTag003	0	239	0	239
	SbTag004	0	325	2	323
	SbTag006	0	117	0	117
	SbTag007	0	185	0	185
	SbTag009	0	117	0	117
	SbTag010	0	175	0	175
	SbTag011	0	179	55	124
	SbTag012	0	88	0	88
	SbTag014	0	281	0	281
	SbTag015	0	175	0	175
	SbTag016	0	193	0	193
	SbTag017	0	119	0	119
	SbTag018	0	216	0	216

Table S2: Number of observations on- and off-range (HRC) for each tagged short-finned pilot whale and rough-toothed dolphin, see Figs S7 and S10.

Species	Range	Transition probabilities
Cuvier's beaked whales	50% range	$\begin{bmatrix} 0.858 & 0.142 \\ 0.119 & 0.881 \end{bmatrix}$
	95% range	$\begin{bmatrix} 0.987 & 0.013 \\ 0.002 & 0.998 \end{bmatrix}$
Fin whales	50% range	$\begin{bmatrix} 0.989 & 0.011 \\ 0.180 & 0.820 \end{bmatrix}$
	95% range	$\begin{bmatrix} 0.962 & 0.038 \\ 0.006 & 0.994 \end{bmatrix}$
Short-finned pilot whales	50% range	$\begin{bmatrix} 0.936 & 0.064 \\ 0.047 & 0.953 \end{bmatrix}$
	95% range	$\begin{bmatrix} 0.938 & 0.062 \\ 0.003 & 0.997 \end{bmatrix}$
Rough-toothed dolphins	50% range	$\begin{bmatrix} 0.705 & 0.295 \\ 0.003 & 0.997 \end{bmatrix}$

Table S3: Raw transition probability matrices for each species, $\mathbf{P}$ with elements p_{ij} $i, j = 1, 2 =$ off- on-range, averaged across individuals who made that particular transition.

Appendix S2: Results

Parameter estimates from the discrete-space continuous-time Markov model discussed in Section Discrete-space continuous-time Markov model are reported in Table S4 for SOCAL and Table S5 for HRC.

As for the AUTEC data, we fitted three models to the tracks of each species; see Section Discrete-space continuous-time Markov model. Where appropriate, $\mathrm{z}_k(t)$ represents the number of days since exposure divided by 10. This simple transformation was used to facilitate the readability of parameter estimates.

Log-likelihood values, AICs, and parameter estimates are reported in Tables S4 and S5. For all species, using either set of range boundaries, the model including only individual random effects (model (b) in Section Discrete-space continuous-time Markov model) offered the best fit. Differently from the AUTEC results, we could not detect an effect of sonar exposure on transition rates for any of the species in SOCAL or HRC: the AIC of models including this effect (Equation (2)) were higher, and the associated parameters, $\hat{\boldsymbol{\beta}}_1 = \{\hat{\beta}_{1,12}, \hat{\beta}_{1,21}\}^T$ and $\hat{\boldsymbol{\beta}}_2 = \{\hat{\beta}_{2,12}, \hat{\beta}_{2,21}\}^T$, had large standard errors.

Given the widespread nature of sonar activities in these regions (compared to the AUTEC range), with exercises regularly occurring beyond the official range boundaries, exposure to sonar (as indicated by $\mathrm{z}(t)$) is likely to be misrepresented in the data when using the 50% boundaries. Therefore, animals could have been exposed to sonar even when they were classified as being off the range. Using a more conservative 95% boundary (with a 100-km buffer), the relative scale of animal movements meant that transitions on–off the ranges were limited. These features of sonar exercises at SOCAL and HRC are likely to interfere with our assessment of the effects of exposure on transition rates, and could have thus contributed to our inability to detect an effect of such exposure on the movement behavior of the four species under analysis. In addition, in the case of Cuvier's beaked whales in SOCAL, previous studies have shown that animals respond to sonar over a smaller spatial and temporal scale compared to observations in AUTEC (Falcone et al., 2017), which, paired with the uncertainty in the boundaries of the target area and the temporal resolution of the telemetry data, could also make it harder to detect changes in attendance following exposure.

	model	random/exposure	$\mathbf{P(t=1)}^*$	log-likelihood	AIC	$\hat{\boldsymbol{\beta}}_0$	$\hat{\boldsymbol{\beta}}_1$	$\hat{\boldsymbol{\beta}}_2$
Cuvier's beaked whales 95% SOCAL range	(a)	-/-	$\begin{bmatrix}0.971 & 0.029\\ 0.006 & 0.994\end{bmatrix}$	-35.70	75.41	$\begin{bmatrix}-3.53\,(0.71)\\ -5.18\,(0.58)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.971 & 0.029\\ 0.006 & 0.994\end{bmatrix}$	-35.70	75.41	$\begin{bmatrix}-3.53\,(0.71)\\ -5.18\,(0.58)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.985 & 0.015\\ 0.001 & 0.999\end{bmatrix}$	-35.17	84.34	$\begin{bmatrix}-4.19\ \ (3.48)\\ -10.47\,(16.36)\end{bmatrix}$	$\begin{bmatrix}0.86\ \ (3.86)\\ 5.56\,(16.37)\end{bmatrix}$	$\begin{bmatrix}4.32\,(14.42)\\ 0.17\ \ (0.71)\end{bmatrix}$
Fin whales 95% SOCAL range	(a)	-/-	$\begin{bmatrix}0.928 & 0.072\\ 0.031 & 0.969\end{bmatrix}$	-336.05	676.10	$\begin{bmatrix}-2.58\,(0.18)\\ -3.42\,(0.16)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.927 & 0.073\\ 0.024 & 0.976\end{bmatrix}$	-332.10	670.20	$\begin{bmatrix}-2.56\,(0.30)\\ -3.67\,(0.28)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.929 & 0.071\\ 0.029 & 0.971\end{bmatrix}$	-332.06	1388.29	$\begin{bmatrix}-2.60\,(0.51)\\ -3.49\,(0.99)\end{bmatrix}$	$\begin{bmatrix}0.08\,(0.62)\\ -0.24\,(1.09)\end{bmatrix}$	$\begin{bmatrix}4.50\,(41.14)\\ 0.75\ \ (1.83)\end{bmatrix}$
Cuvier's beaked whales 50% SOCAL range	(a)	-/-	$\begin{bmatrix}0.884 & 0.116\\ 0.192 & 0.808\end{bmatrix}$	-360.81	725.62	$\begin{bmatrix}-1.98\,(0.15)\\ -1.47\,(0.14)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.831 & 0.169\\ 0.257 & 0.743\end{bmatrix}$	-323.41	652.81	$\begin{bmatrix}-1.51\,(0.50)\\ -1.10\,(0.53)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.843 & 0.157\\ 0.211 & 0.789\end{bmatrix}$	-322.90	659.80	$\begin{bmatrix}-1.63\,(0.05)\\ -1.34\,(0.64)\end{bmatrix}$	$\begin{bmatrix}0.16\,(\quad)\\ 0.58\,(0.53)\end{bmatrix}$	$\begin{bmatrix}0.38\,(\quad)\\ 1.95\,(3.60)\end{bmatrix}$
Fin whales 50% SOCAL range	(a)	-/-	$\begin{bmatrix}0.967 & 0.033\\ 0.516 & 0.484\end{bmatrix}$	-508.45	1020.89	$\begin{bmatrix}-3.04\,(0.14)\\ -0.29\,(0.12)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.974 & 0.026\\ 0.609 & 0.391\end{bmatrix}$	-492.12	990.24	$\begin{bmatrix}-3.19\,(0.25)\\ -0.03\,(0.27)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.961 & 0.039\\ 0.658 & 0.342\end{bmatrix}$	-489.90	993.8	$\begin{bmatrix}-2.71\,(0.40)\\ 0.12\,(0.30)\end{bmatrix}$	$\begin{bmatrix}-0.98\,(0.54)\\ -0.72\,(0.60)\end{bmatrix}$	$\begin{bmatrix}0.89\,(0.63)\\ 4.74\,(3.74)\end{bmatrix}$

Table S4: Table of estimated parameters, log-likelihood, and AIC values for each model fitted to Cuvier's beaked and fin whale data from the SOCAL range (standard errors in brackets; empty if standard errors returned as NAN). The first column gives the model number as discussed in Section Discrete-space continuous-time Markov model. The second column indicates if the model includes individual random effects (random) or an exposure component (exposure). For example, +/+ indicates that a model includes both components. The baseline transition rates, on the log scale, are given by $\hat{\boldsymbol{\beta}}_0 = \{\hat{\beta}_{0,12}, \hat{\beta}_{0,21}\}^T$. Where applicable, the changes in transition rate during exposure are given by $\hat{\boldsymbol{\beta}}_1 = \{\hat{\beta}_{1,12}, \hat{\beta}_{1,21}\}^T$ and the decay parameters are given by $\hat{\boldsymbol{\beta}}_2 = \{\hat{\beta}_{2,12}, \hat{\beta}_{2,21}\}^T$. * denotes that $\mathbf{P(t=1)}$ is calculated at the baseline transition rate (i.e., ignoring any other effects, if there are any).

	model	random/exposure	$\mathbf{P(t=1)}^*$	log-likelihood	AIC	$\hat{\boldsymbol{\beta}}_0$	$\hat{\boldsymbol{\beta}}_1$	$\hat{\boldsymbol{\beta}}_2$
Short-finned pilot whales 95% HRC range	(a)	-/-	$\begin{bmatrix}0.869 & 0.131\\0.012 & 0.988\end{bmatrix}$	-81.03	166.06	$\begin{bmatrix}-1.95\ (0.45)\\-4.38\ (0.35)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.823 & 0.177\\0.001 & 0.999\end{bmatrix}$	-72.81	151.63	$\begin{bmatrix}-1.63\ (1.69)\\-6.42\ (1.57)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.436 & 0.564\\0.001 & 0.999\end{bmatrix}$	-69.30	152.61	$\begin{bmatrix}-0.19\ (2.41)\\-7.15\ (1.95)\end{bmatrix}$	$\begin{bmatrix}-11.21\ (14.20)\\1.48\ (1.09)\end{bmatrix}$	$\begin{bmatrix}34.3\ (24.5)\\1485.9\ (6176.3)\end{bmatrix}$
Short-finned pilot whales 50% HRC range	(a)	-/-	$\begin{bmatrix}0.697 & 0.313\\0.197 & 0.803\end{bmatrix}$	-735.44	1474.88	$\begin{bmatrix}-0.82\ (0.10)\\-1.29\ (0.10)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.681 & 0.319\\0.177 & 0.823\end{bmatrix}$	-689.34	1384.68	$\begin{bmatrix}-0.82\ (0.27)\\-1.41\ (0.25)\end{bmatrix}$	-	-
	(c)	+/+	$\begin{bmatrix}0.749 & 0.251\\0.032 & 0.968\end{bmatrix}$	-687.15	1388.29	$\begin{bmatrix}-1.22\ (1.22)\\-3.28\ (4.01)\end{bmatrix}$	$\begin{bmatrix}0.44\ (1.26)\\2.08\ (4.00)\end{bmatrix}$	$\begin{bmatrix}0.39\ (1.50)\\0.29\ (0.65)\end{bmatrix}$
Rough-toothed dolphins 50% HRC range	(a)	-/-	$\begin{bmatrix}0.211 & 0.789\\0.017 & 0.983\end{bmatrix}$	-56.02	116.04	$\begin{bmatrix}0.47\ (0.41)\\-3.36\ (0.41)\end{bmatrix}$	-	-
	(b)	+/-	$\begin{bmatrix}0.022 & 0.978\\0.001 & 0.999\end{bmatrix}$	-49.52	105.04	$\begin{bmatrix}1.36\ (1.76)\\-5.33\ (1.62)\end{bmatrix}$	-	-

Table S5: Table of estimated parameters, log-likelihood, and AIC values for each model fitted to short-finned pilot whale and rough-toothed dolphin data from the HRC range (standard errors in brackets). The first column gives the model number as discussed in Section Discrete-space continuous-time Markov model. The second column indicates if the model includes individual random effects (random) or an exposure component (exposure). For example, +/+ indicates that a model includes both components. The baseline transition rates, on the log scale, are given by $\hat{\boldsymbol{\beta}}_0 = \{\hat{\beta}_{0,12}, \hat{\beta}_{0,21}\}^T$. Where applicable, the changes in transition rate during exposure are given by $\hat{\boldsymbol{\beta}}_1 = \{\hat{\beta}_{1,12}, \hat{\beta}_{1,21}\}^T$ and the decay parameters are given by $\hat{\boldsymbol{\beta}}_2 = \{\hat{\beta}_{2,12}, \hat{\beta}_{2,21}\}^T$. * denotes that $\mathbf{P(t=1)}$ is calculated at the baseline transition rate (i.e., ignoring any other effects, if there are any).

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