Ecography

ECOG-04463

Byrne, M. E., Vaudo, J. J., Harvey, G. C. McN., Johnston, M. W., Wetherbee, B. M. and Shivji, M. 2019. Behavioral response of a mobile marine predator to environmental variables differs across ecoregions. – Ecography doi: 10.1111/ecog.04463

Appendix 1

Tagging information for shortfin mako sharks *Isurus oxyrinchus* tagged off the Yucatan Peninsula and the east coast of North America during 2013–2015.

ID	Location	Sex	Fork length (cm)	Deployment year	Deployment date	Tracking duration (d)	Argos locations
1	Yucatan	F	180	2013	23 Mar	411	1408
2	Yucatan	F	175	2013	25 Mar	297	608
3	Yucatan	F	250	2013	8 Apr	293	581
4	Yucatan	M	175	2013	8 Apr	211	120
5	Yucatan	M	186	2014	21 Mar	125	519
6	Yucatan	F	148	2014	22 Mar	527	963
7	Yucatan	M	193	2014	23 Mar	325	1287
8	Yucatan	M	195	2014	24 Mar	138	357
9	Yucatan	M	179	2014	24 Mar	520	1447
10	Yucatan	M	193	2014	25 Mar	523	979
11	Yucatan	M	178	2014	25 Mar	494	1324
12	Yucatan	F	252	2014	29 Mar	203	560
13	Yucatan	F	180	2015	12 Apr	201	137
14	East Coast	M	168	2013	27 May	98	670
15	East Coast	F	175	2013	28 May	317	2022
16	East Coast	M	172	2013	28 May	251	1444
17	East Coast	M	198	2013	28 May	89	579
18	East Coast	M	155	2013	31 May	404	1912
19	East Coast	M	153	2014	17 May	357	1590
20	East Coast	M	155	2014	19 May	468	1468
21	East Coast	F	178	2014	19 May	468	1693
22	East Coast	F	188	2014	20 May	379	1106
23	East Coast	M	179	2014	20 May	438	907
24	East Coast	M	150	2014	20 May	357	538
25	East Coast	M	180	2014	21 May	112	357
26	East Coast	M	192	2014	22 May	78	281
27	East Coast	M	128	2014	11 Sep	394	670
28	East Coast	F	158	2015	15 May	49	180
29	East Coast	M	117	2015	19 May	163	373
30	East Coast	M	121	2015	19 May	81	186
31	East Coast	M	158	2015	19 May	165	492

32	East Coast	M	158	2015	23 May	161	379
33	East Coast	F	122	2015	24 May	160	246
34	East Coast	M	143	2015	25 May	159	854
35	East Coast	M	156	2015	26 May	158	626
36	East Coast	F	167	2015	27 May	157	1310
37	East Coast	M	192	2015	27 May	157	918
38	East Coast	M	175	2015	31 May	85	457
39	East Coast	F	147	2015	20 June	111	319

Appendix 2

The process model portion of the SSM is based on a first-difference correlated random walk for two behavioral states, specified as in Jonsen et al. (2007) as:

$$\mathrm{d}_t \sim N_2[\gamma_{bt} \mathrm{T}(\theta_{bt}) \mathrm{d}_{t-1}, \Sigma]$$

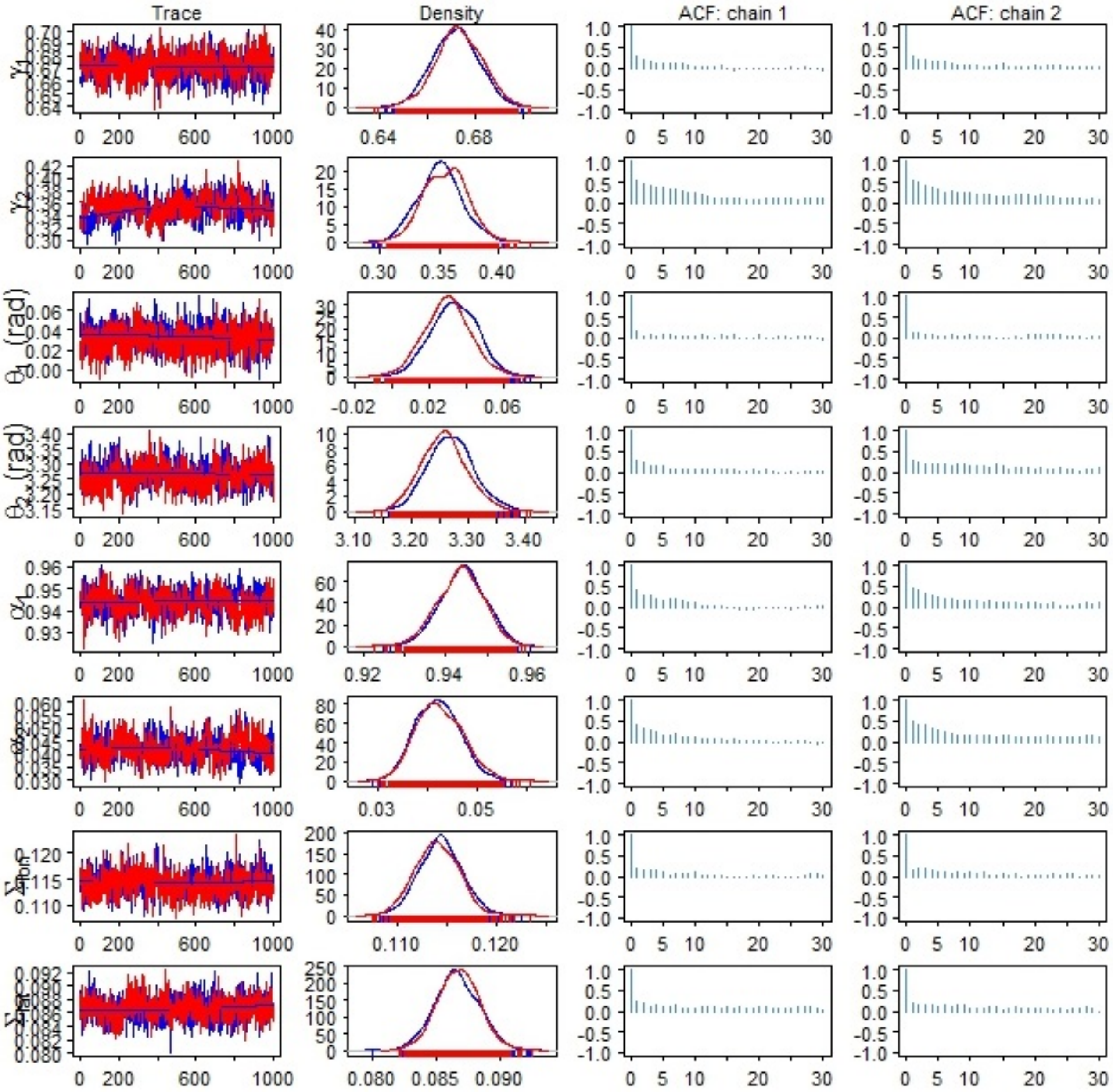
where $\mathrm{d}_{t\text{-}1}$ is the difference between the location at time t-1 and t-2, $\mathbf{d}_t$ is the difference between the locations at time t and t-1, N_2 is a bivariate Gaussian distribution with covariance matrix Σ representing the randomness in the animal's behavior. Key behavior parameters are $\mathbf{T}(\theta)$, which is a transition matrix providing the rotation required to move from $\mathbf{d}_{t\text{-}1}$ to $\mathbf{d}_t$, where θ is the mean turning angle, and γ is a value between 0 – 1 representing autocorrelation in speed and direction. The behavioral modes, nominally corresponding to "transiting" and "resident" behavior, are indicated by the index $_{bt}$. Thus, the two parameters controlling movement, θ and γ, should have different values for each behavioral mode. For transiting behavior, a shark traveling in a directed manner, expected mean turning angles are close to 0^{o} with high correlation in speed and direction. The opposite is true for resident behavior, which is characterized by slower speeds and more frequent turns. Additional parameters handle switching between behaviors; with α_1 representing the probability of being in a transiting state at time t given transiting state at time t – 1, and α_2 is the probability of switching to a transiting state given resident state at time t – 1. Spatial error associated with Argos location classes was used to inform the observation model based on estimated reported in Vincent et al. (2002). For more detail on model formulation and implementation see:

Jonsen, I. 2016. Joint estimation over multiple individuals improves behavioural state inference from animal movement data. – Sci. Rep. 6: 20625

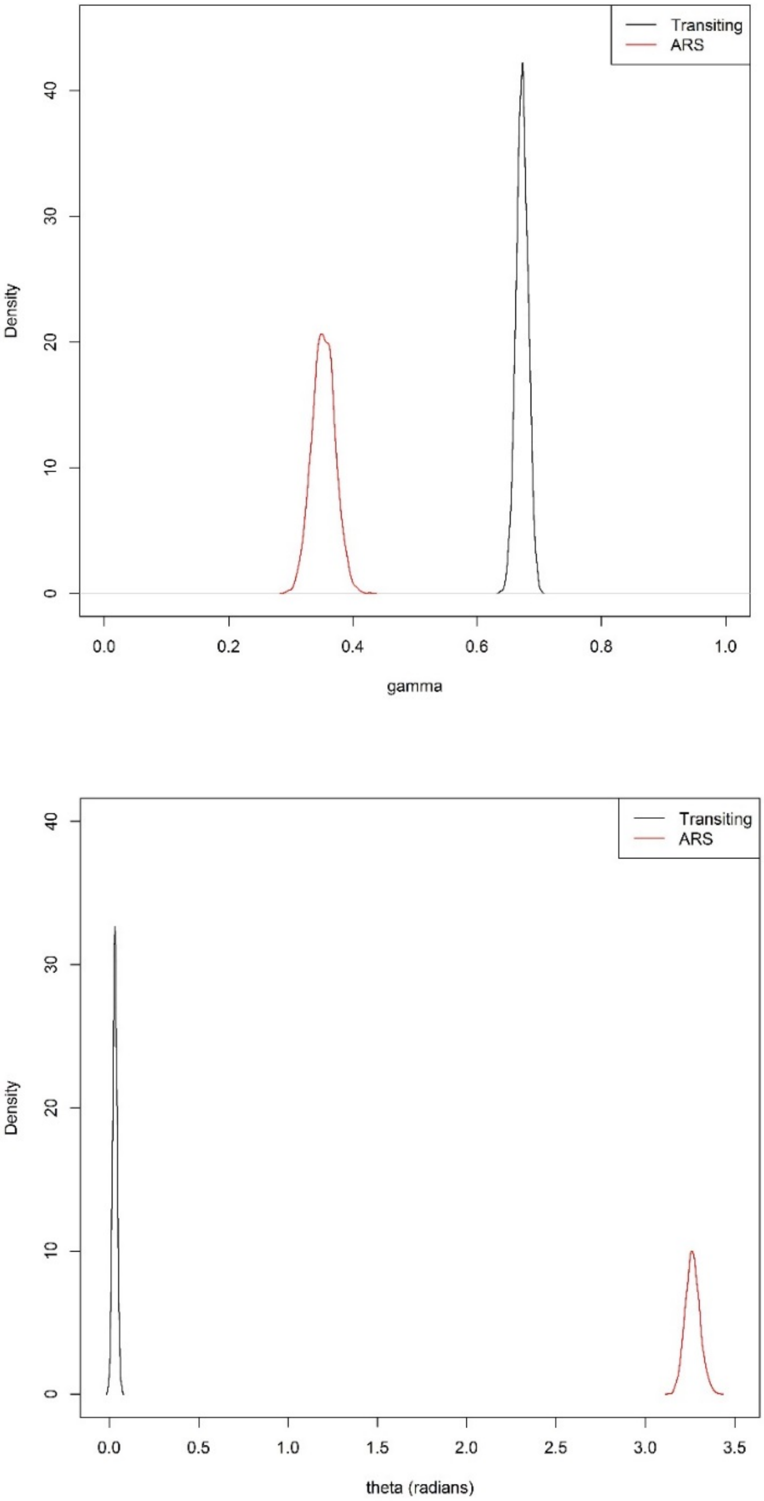
Jonsen, I. D. et al. 2005. Robust state-space modeling of animal movement data. – Ecology 86: 2874–2880.

Jonsen, I. D. et al. 2007. Identifying leatherback turtle foraging behavior from satellite telemetry using a switching state-space model. – Mar. Ecol. Progr. Ser. 337: 255–264.

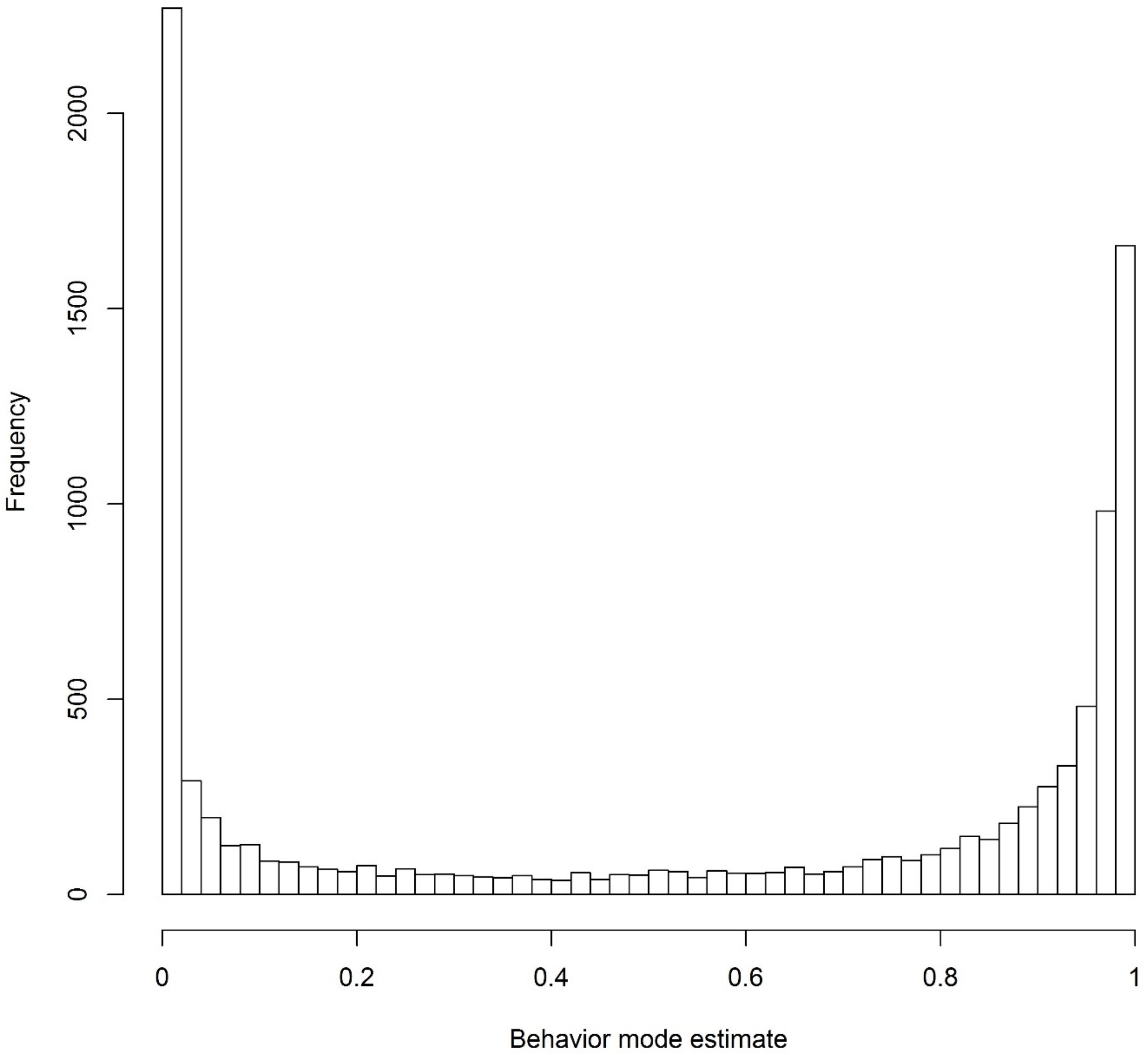
Vincent, C. et al. 2002. Assessment of Argos location accuracy from satellite tags deployed on captive grey seals. – Mar. Mamm. Sci. 18: 156–166.



MCMC diagnostics for hierarchical Bayesian state space model. Different colors identify individual MCMC chains.



Posterior probability distributions for movement parameters of autocorrelation in speed and direction (γ) and turning angle (θ) for transiting and resident (ARS) behavioral models



Histogram of estimated behavioral modes (proportion of MCMC samples classified as resident behavior) for daily SSM locations. Increasing values correspond to increasing probability of a daily location representing resident behavior. Values ≤ 0.3 were considered transiting, and values ≥ 0.7 were considered resident.

Appendix 3

Habitat model information

Table A3-1. Akaike's information criterion (AIC) results of mixed-effects models evaluating several functional relationships between habitat variables and probability of mako shark resident behavior in the open west North Atlantic Ocean. If any functional relationships were ≥ 2 ΔAIC units from the linear form, we considered the form with the lowest AIC value to be the most supported and included that functional form in the final model (italicized in table).

Habitat variable	Functional relationship	AIC	ΔAIC[1]
Depth	Linear	23237.82	0
	Quadratic	*23228.28*	*-9.54*
	Logarithmic	23247.66	9.84
	Exponential	23244.62	6.80
Slope	*Linear*	*23249.89*	*0*
	Quadratic	23248.21	-1.68
	Logarithmic	23252.62	2.73
	Exponential	23251.80	1.92
SST	Linear	23230.51	0
	Quadratic	*23213.52*	*-16.99*
	Logarithmic	23222.42	-8.08
	Exponential	23246.99	16.48
PP	Linear	23235.17	0
	Quadratic	23226.96	-8.22
	Logarithmic	*23218.85*	*-16.32*
	Exponential	23254.19	19.01
SSH_g	*Linear*	*23245.13*	*0*
	Quadratic	23246.73	1.60
	Logarithmic	23248.51	3.38
	Exponential	23254.19	9.06

[1] Relative to linear model

The final habitat model for the open western North Atlantic was as follows:

$$\ln\left(\frac{state_t}{1-state_t}\right) \sim \beta_0 + \beta_1 Depth + \beta_2 Depth^2 + \beta_3 Slope + \beta_4 SST + \beta_5 SST^2 + \beta_6 \log(PP) +$$

$$\beta_7 SSH_g + \phi \ln\left(\frac{state_{t-1}}{1-state_{t-1}}\right) + v_i + \varepsilon$$

where $state_t$ is the probability of resident behavior at time t, β's are fixed-effects regression coefficients, φ represents the AR1 autocorrelation coefficient, and v_i is the random effect of the *i*th mako shark.

Table A3-2. Fixed effects parameter estimates for the full random effects model evaluating the effect of environmental covariates on the probability of resident behavior for mako sharks in the western North Atlantic Ocean.

Covariate	β	Lower 95% CI	Upper 95% CI
Depth	0.21	0.03	0.39
Depth^2	-0.06	-0.10	-0.03
Slope	0.022	-0.009	0.053
SST	-0.65	0.88	-0.43
SST^2	0.016	0.010	0.43
Log(PP)	0.44	0.23	0.61
SSH$_g$	-0.028	-0.054	-0.002

Table A3-3. Akaike's information criterion (AIC) results of mixed-effects models evaluating several functional relationships between habitat variables and probability of mako shark resident behavior in the Caribbean/Gulf of Mexico. If any functional relationships were ≥ 2 ΔAIC units from the linear form, we considered the form with the lowest AIC value to be the most supported and included that functional form in the final model (italicized in table).

Habitat variable	Functional relationship	AIC	ΔAIC[1]
Depth	*Linear*	*8785.747*	*0*
	Quadratic	8787.745	2.00
	Logarithmic	8798.891	13.14
	Exponential	8801.349	15.60
Slope	Linear	8799.292	0
	Quadratic	8795.337	-3.95
	Logarithmic	8801.291	2.00
	Exponential	*8794.347*	*-4.95*
SST	*Linear*	*8800.686*	*0*
	Quadratic	8801.567	0.88
	Logarithmic	8800.500	-0.19
	Exponential	8799.650	-1.04
PP	*Linear*	*8800.675*	*0*
	Quadratic	8801.248	0.57
	Logarithmic	8799.229	-1.45
	Exponential	8799.773	-0.90
SSH$_g$	*Linear*	*8796.096*	*0*
	Quadratic	8796.638	0.54
	Logarithmic	8799.370	3.27
	Exponential	8801.433	5.34

[1] Relative to linear model

The final habitat model for the Caribbean/Gulf of Mexico was as follows:

$$\ln\left(\frac{state_t}{1-state_t}\right) \sim \beta_0 + \beta_1 Depth + \beta_2 \exp(Slope) + \beta_3 SST + \beta_4 PP + \beta_5 SSH_g$$

$$+\phi \ln\left(\frac{state_{t-1}}{1-state_{t-1}}\right) + v_i + \varepsilon$$

where $state_t$ is the probability of resident behavior at time t, β's are fixed-effects regression coefficients, φ represents the AR1 autocorrelation coefficient, and v_i is the random effect of the *i*th mako shark.

Table A3-4. Fixed effects parameter estimates for the full random effects model evaluating the effect of environmental covariates on the probability of resident behavior for mako sharks in the western North Atlantic Ocean.

Covariate	β	Lower 95% CI	Upper 95% CI
Depth	-0.102	-0.151	-0.052
exp(Slope)	-0.00000028	-0.00000049	-0.00000007
SST	-0.03	-0.10	0.03
PP	0.02	-0.05	0.09
SSH_g	0.04	0.01	0.06