Online Resource 2 – Supporting results

At-sea distribution and foraging tactics in a monomorphic tropical seabird

Authors

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Evidence for dual foraging during chick rearing.

During the chick rearing period, Wedge-tailed Shearwaters (WTS) implemented a dual foraging tactic (Fig. S1) where they executed multiple short foraging trips followed by a single long foraging trip (Fig. S1). Short trips were closer to the colony (< 200 km) than long foraging trips (Fig. S2).

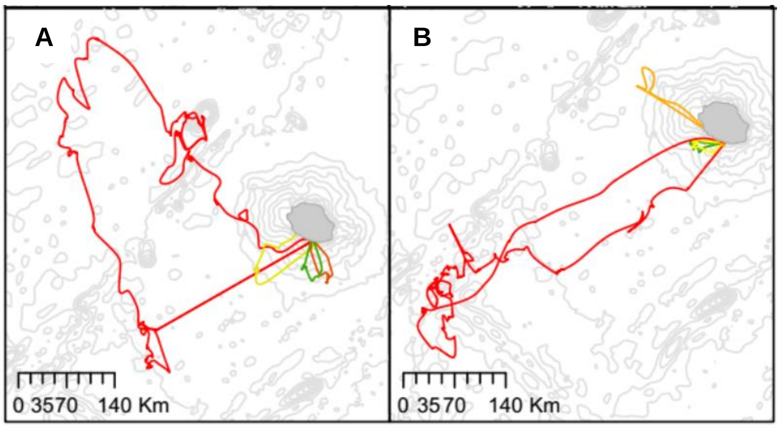

Fig. S1 Examples of foraging trips where individual Wedge-tailed Shearwaters made several short trips and single long trips during chick rearing (2016/17), indicative of a dual foraging tactic. Each foraging trip is denoted by a different colour, and long foraging trips are indicated by the red line.

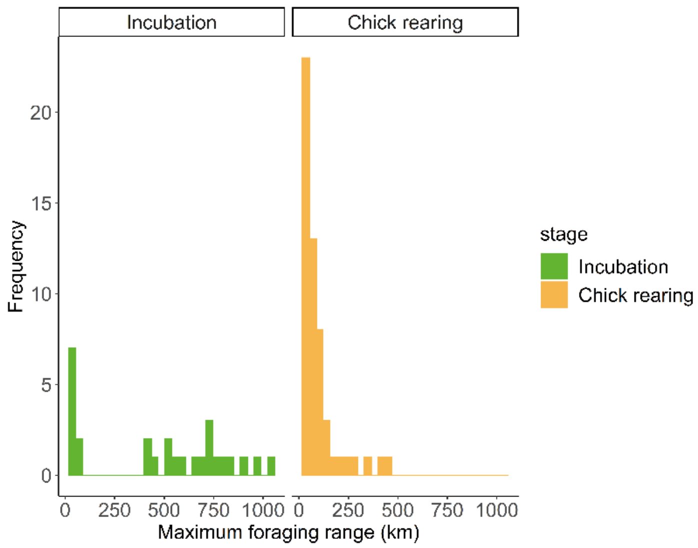

Fig. S2 Frequency distribution of the maximum foraging range for all the foraging trips of Wedge-Tailed Shearwaters during chick rearing and incubation.

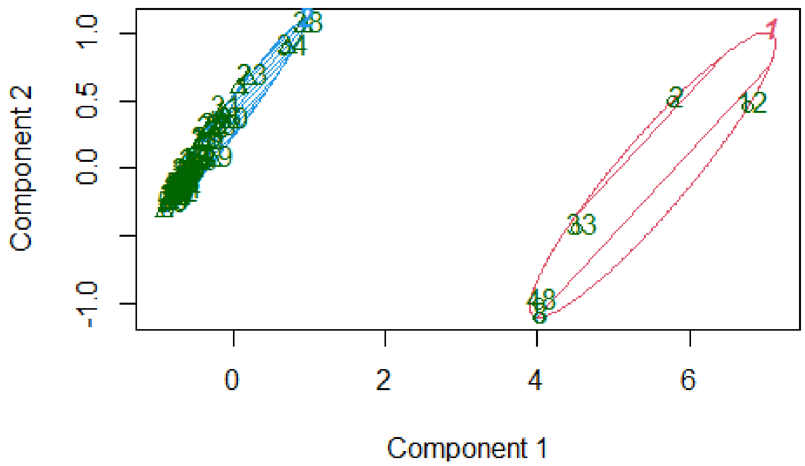

Fig. S3 K-Means clustering with 2 clusters plotted against the first and second principal components. The two components explain 97.71% of the point variability.

Behaviour classification

Behaviours from GPS tracks were inferred using the expectation-maximization binary clustering ('EMbC' in the package EMbC; Garriga et al. 2016). Based on the assumption that foraging can be identified by area restricted search (ARS) behaviours, where birds make wide turning angles between locations, and that travel/commuting movements are associated with fast and straight stints (Garriga et al. 2016), behaviour labels were accordingly assigned to the movement clusters and included: intensive searching (low velocity/high turning angle), extensive searching (high velocity/high turning angle), travelling/commuting (high velocity/low turning angle), and resting (low velocity/low turning angle; Fig. S4 and S5).

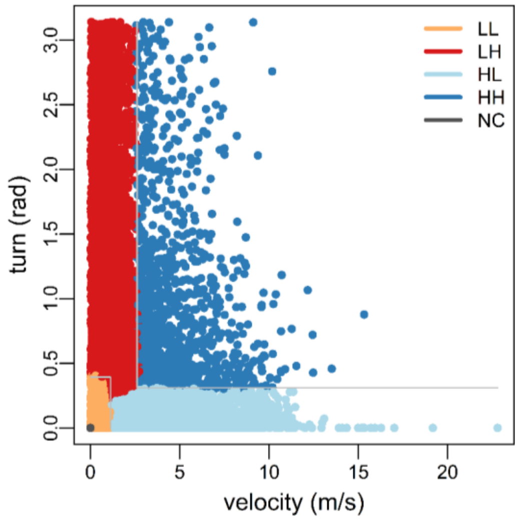

Fig. S4 The classification of behaviour clusters of the GPS coordinates of Wedge-tailed Shearwaters' foraging trips. Behaviour clusters are assigned to the movement clusters and include intensive searching (low velocity/high turning angle; LH), extensive searching (high velocity/high turning angle; HH), travelling/commuting (high velocity/low turning angle; HL), and resting (low velocity/low turning angle; LL). Data points that are not classified are denoted as NC.

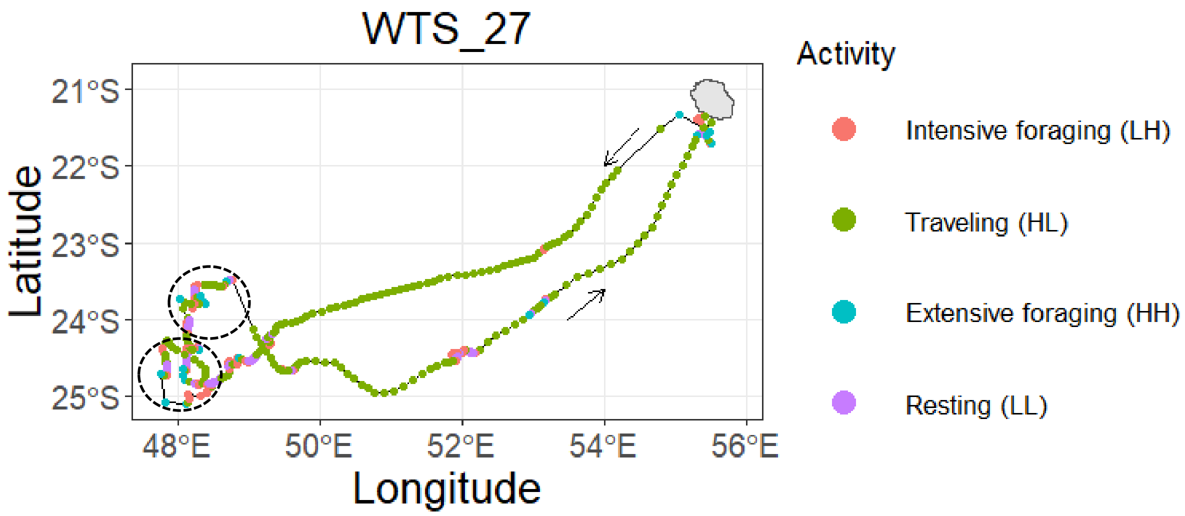

Fig. S5 Example of different behaviours identified using an individual Wedge-Tailed Shearwater (WTS_27) foraging trip. The black arrows indicate the direction of the flight path and dashed circles signify areas with typical area restricted search (ARS) behaviour.

Intensive search behaviours of WTS were identified and were classified as ‘foraging’ locations and are specified on Fig. S6.

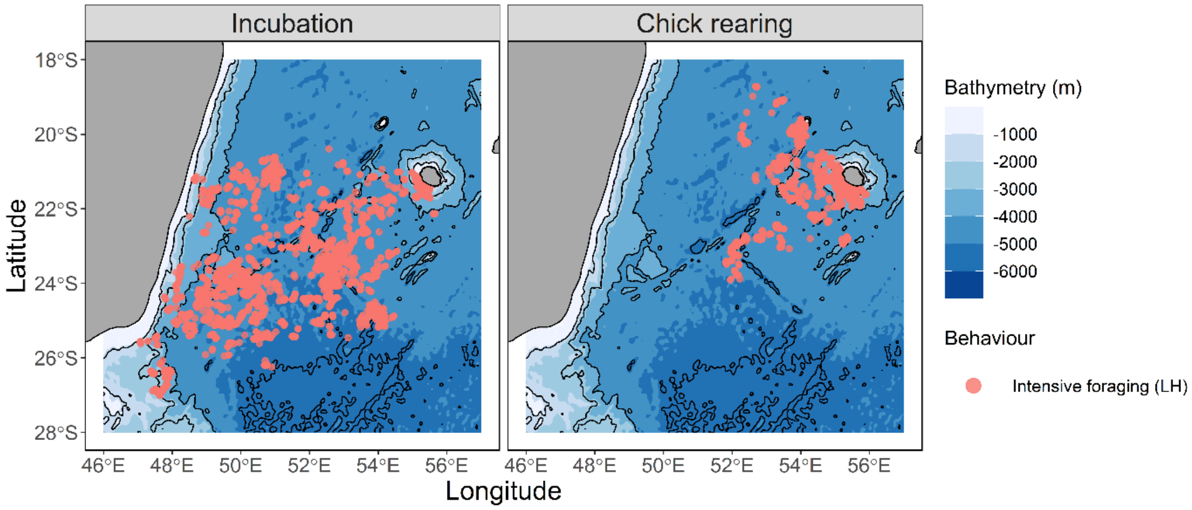

Fig. S6 Location of intesive behaviours identified (for all foraging trips) of Wedge-Tailed Shearwaters breeding on Réunion Island during incubation (left) and early chick rearing (right).

Differences between sexes

Throughout both breeding stages, there were no difference in the proportion of time different sexes implement various foraging behaviours ($p > 0.05$; Fig. S7).

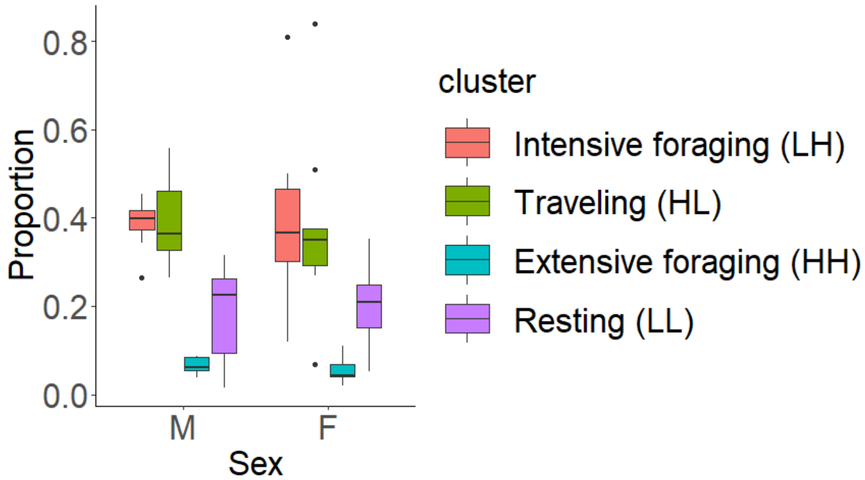

Fig. S7 The proportion of at-sea behaviours that were identified and classified for male and female Wedge-Tailed Shearwater tracked from Réunion Island during the incubation and chick rearing period. There were no differences between foraging behaviours between sexes (GLM, multicomp with Bonferonni procedure, $P > 0.05$).

There was no significant sexual segregation between sexes (Fig. S8). Using a randomization technique, it was shown that the overlap in UD between males and females was not significantly lower than the null expectation for both the core area or home ranges during incubation and chick rearing (P > 0.05).

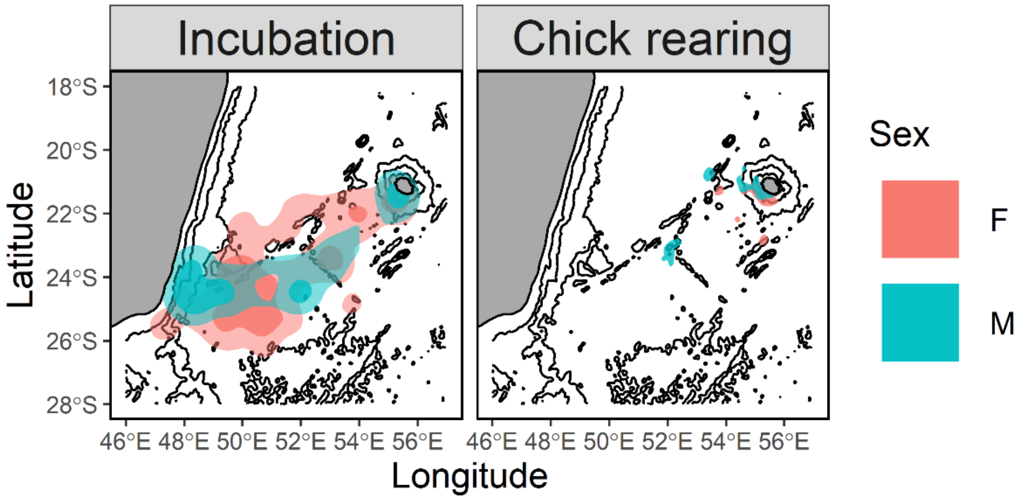

Fig. S8 The core use area and home range (kernel utilization distribution 50% and 90% respectively) of Wedge-Tailed Shearwaters (WTS) breeding on Réunion Island during incubation (male n = 5, female n = 10) and chick rearing (male n =7, female n = 7).

In terms of habitat preferences, during incubation (Fig. S9) and chick rearing (Fig. S10) the most parsimonious model (ΔAICc ≤ 2) included all the environmental variables. Yet, the model had a low overall explanatory power (Deviance Explained, DE = 9.89 %) in predicting foraging probability between sexes. Nevertheless, during incubation both male and female WTS were more likely to forage in deep waters (>1080 m), and less likely in areas with relatively high productivity. During incubation, male WTSs, but not females, were more likely to forage in warmer waters, areas with steep bathymetric gradients and areas depicted by positive sea surface height anomalies (indicative of anticyclonic mesoscale eddies). Females' foraging probability was positively affected by deeper MLD (Fig. S9). For the chick rearing period, the environmental variables also had a low explanatory power (DE = 11.0%) predicting foraging probability between sexes. During chick rearing, male and female WTS' foraging probability was higher in relatively shallower coastal waters (~28 – 49 m), however, males were also more likely to forage over deeper waters, relatively higher CHLA concentrations, and areas associated with both positive and negative SSHA (indicative of anticyclonic and cyclonic mesoscale eddies). Females' foraging probability increased with greater steeper bathymetric gradients and MLD (30 – 35m; Fig. S9 and S10). However, sex was not a significant factor (P > 0.05) when determining habitat preferences within different breeding stages. However, since evidence for spatial segregation were no different than random, differences between sexes are likely to occur due to low sample sizes.

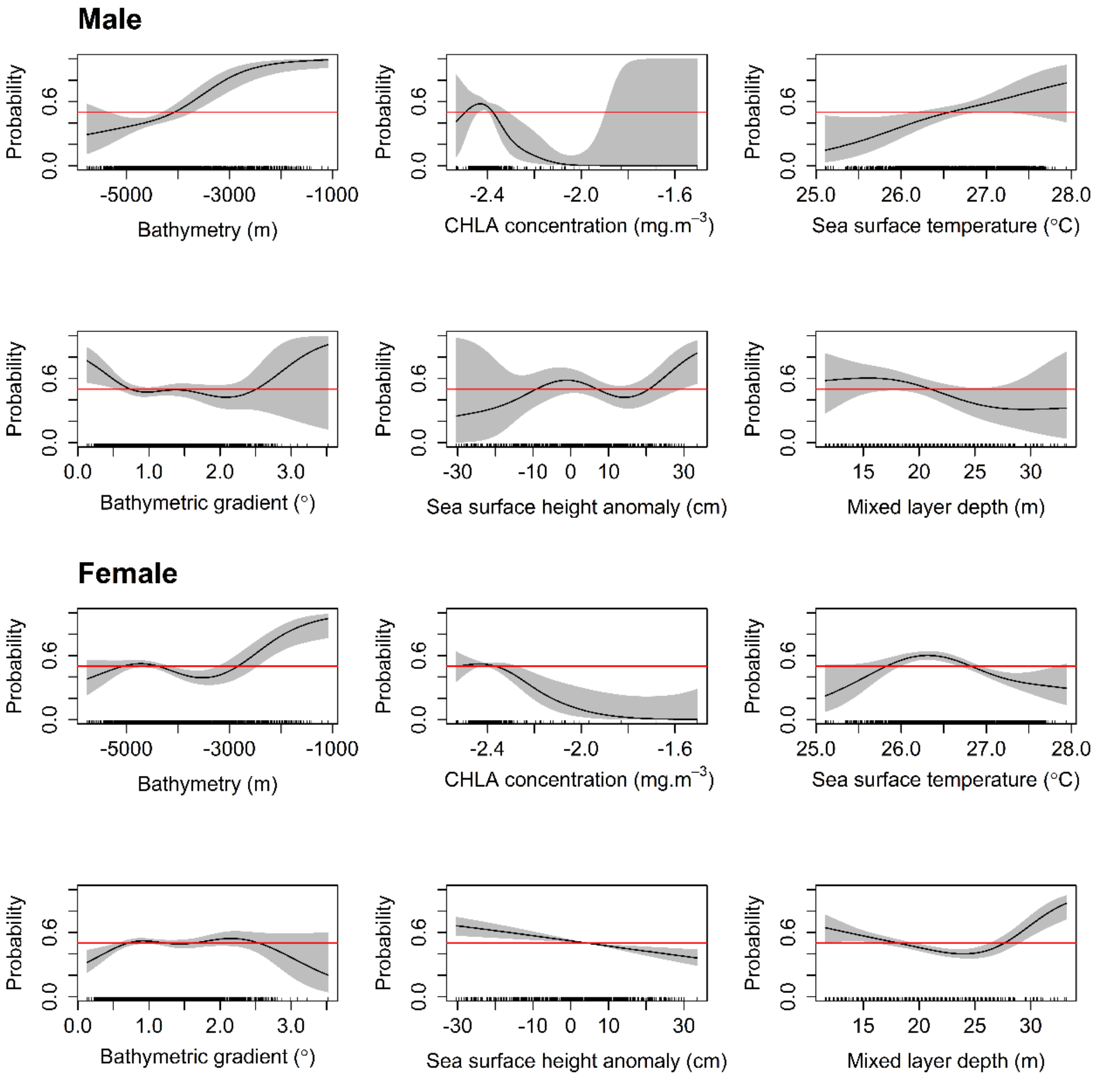

Fig. S9 Response curves for generalized additive models (GAMs) of the probability of incubating male or female Wedge-Tailed Shearwaters foraging according to environmental variables from the best fitted GAMMs (AIC ≤ 2). Chlorophyll *a* concentrations (CHLA) were log transformed and bathymetric gradients were square root transformed. The red line indicates when foraging and non-foraging are equally likely to occur. Deviance explained = 11.7%

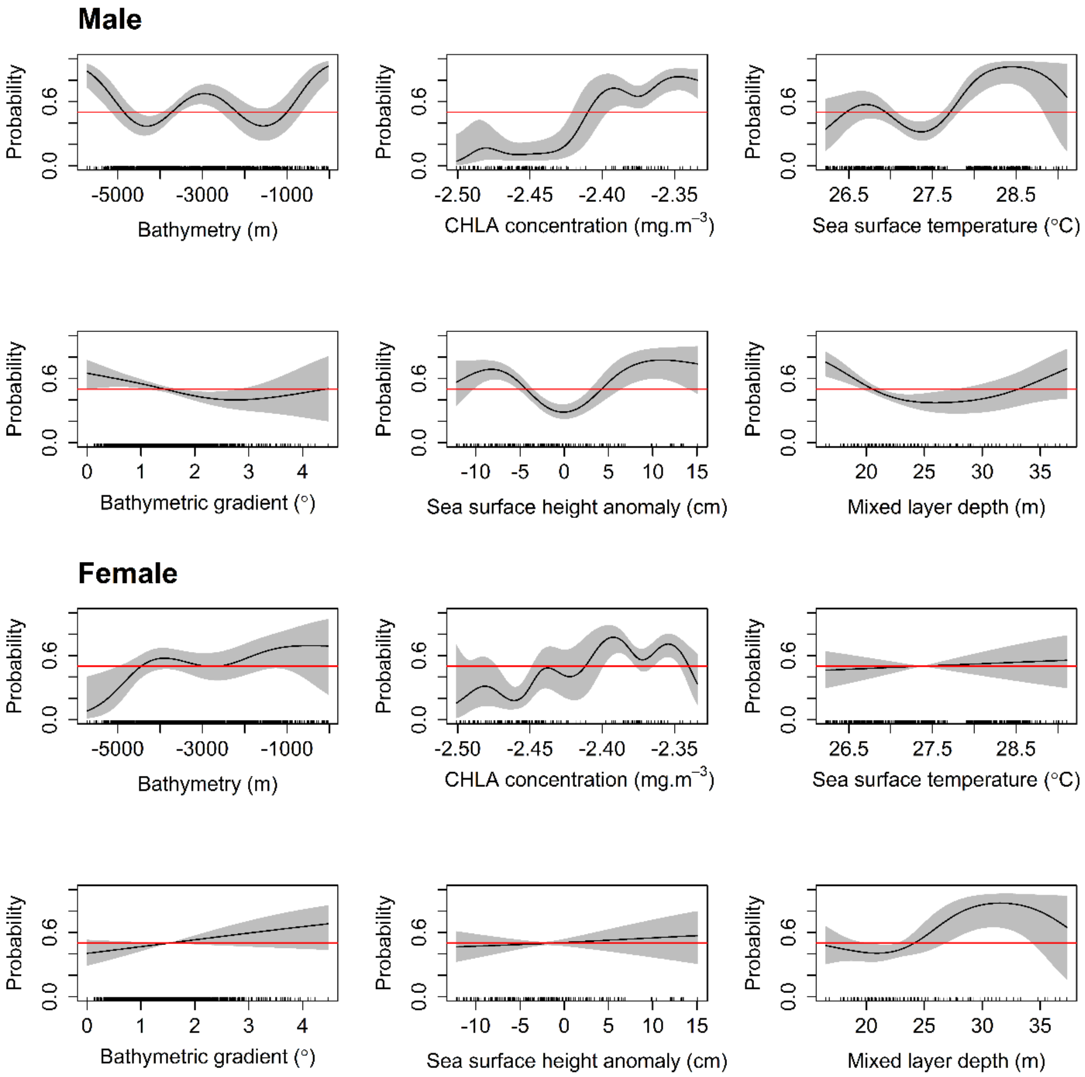

Fig. S10 Response curves for generalized additive models (GAMs) of the probability of chick rearing male or female Wedge-Tailed Shearwaters foraging according to environmental variables from the best fitted GAMMs (AIC ≤ 2). Chlorophyll *a* concentrations (CHLA) were log transformed and bathymetric gradients were square root transformed. The red line indicates when foraging and non-foraging are equally likely to occur. Deviance explained = 9.49%

Sample sizes and correlations

As per Lascelles et al. (2016), saturation curves based on the 50 % UD and 90 % UD were used to determine whether our sample size was representative of the population breeding on Réunion Island. Sample sizes used to estimate core use and home range areas were representative of the population (Fig. S11)

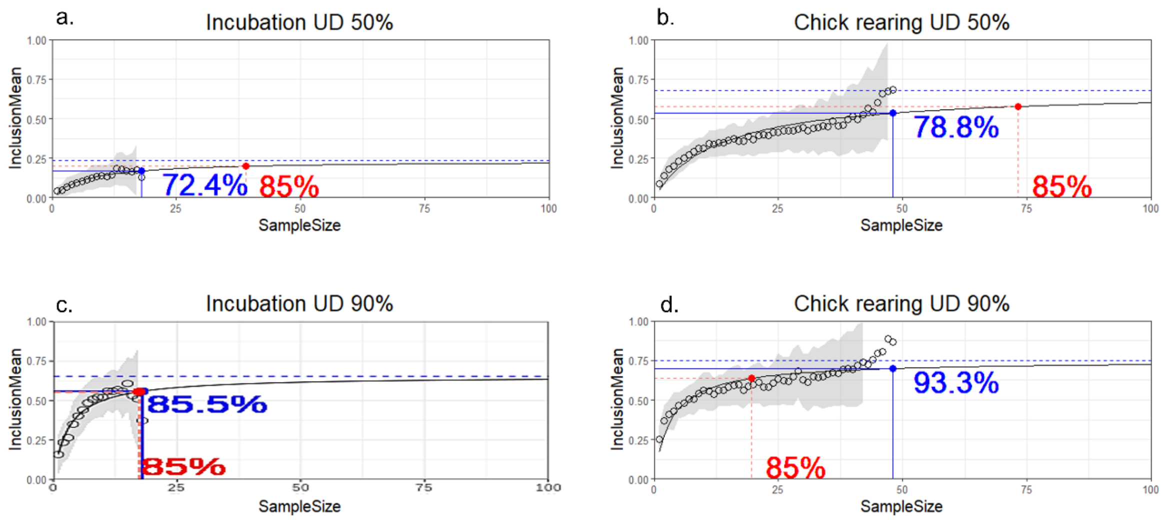

Fig. S11 The representative values of the Wedge-Tailed Shearwater trips during incubation (left) and chick rearing (right). The graphs indicated what proportion of out-of-sample locations are located within the 50% core use and 90% home range areas. Variability of inclusion value for the 100 random data selections are indicated by the grey areas and the nonlinear regression line is represented by the solid line. Values greater than 85 % (indicated by the dashed line) are considered highly representative of the colony tracked. Sample size representivness is highlighted by the solid blue lines and percentages.

None of the environmental variables included in the models were correlated (Pearson's r <|0.5; Fig. S12).

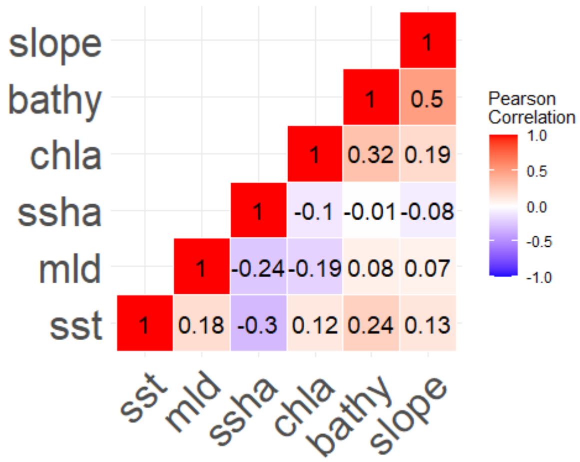

Fig. S12 Results of Pearson Correlation used to compare environmental covariates.

Dual foraging

Wedge-tailed Shearwaters implemented a dual foraging tactic during chick rearing. Birds' foraging probability during long and short trips varied in response to different environmental variables (Fig. S13 – S15).

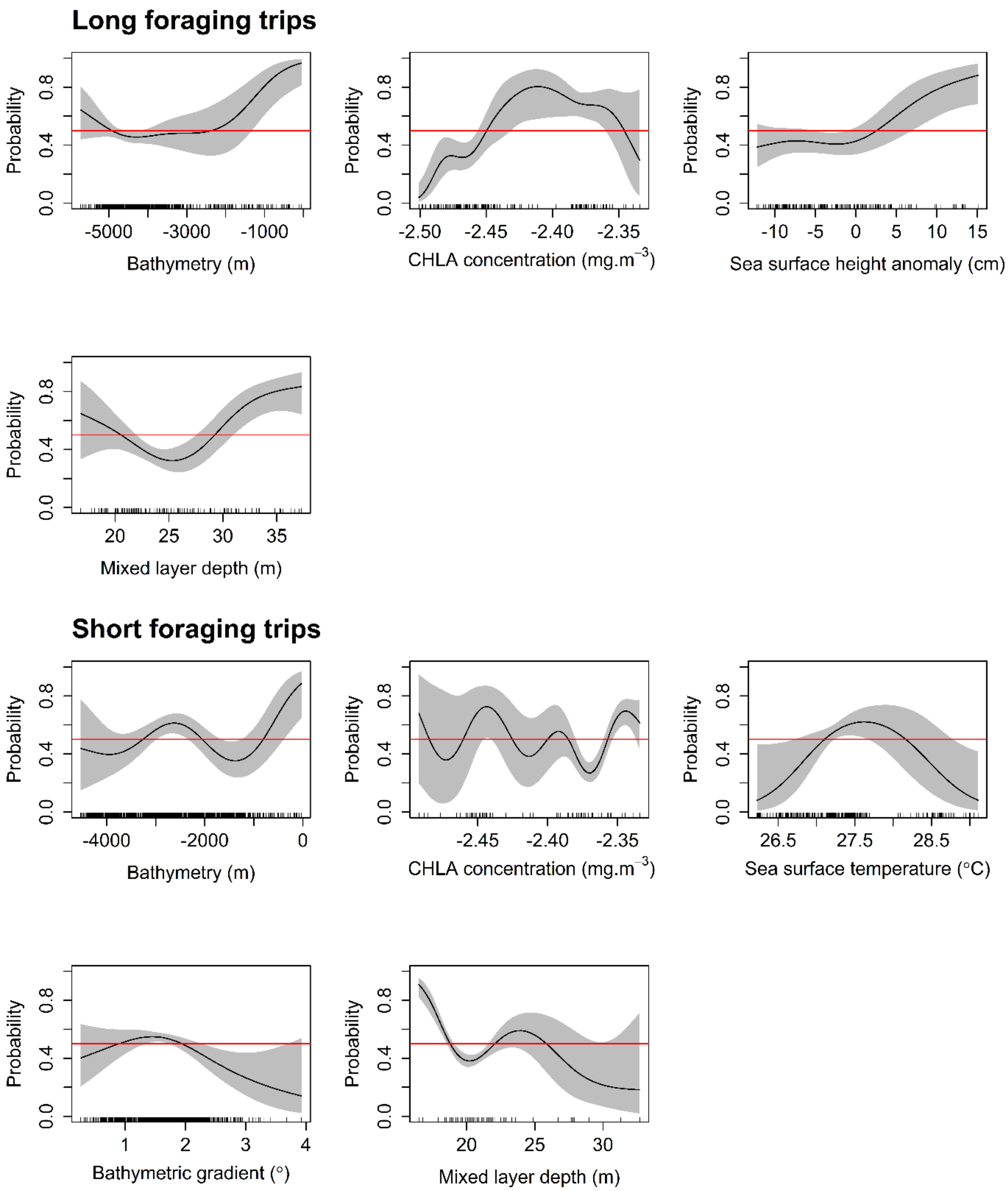

Fig. S13 Response curves for generalized additive models (GAMs) of the probability of chick rearing Wedge-Tailed Shearwaters foraging during long (deviance explained = 13.4) and short (deviance explained = 11.4%) foraging trips according to environmental variables from the best fitted GAMMs (AIC ≤ 2). Chlorophyll *a* concentrations (CHLA) were log transformed and bathymetric gradients were square root transformed. The red line indicates when foraging and non-foraging behaviours are equally likely to occur.

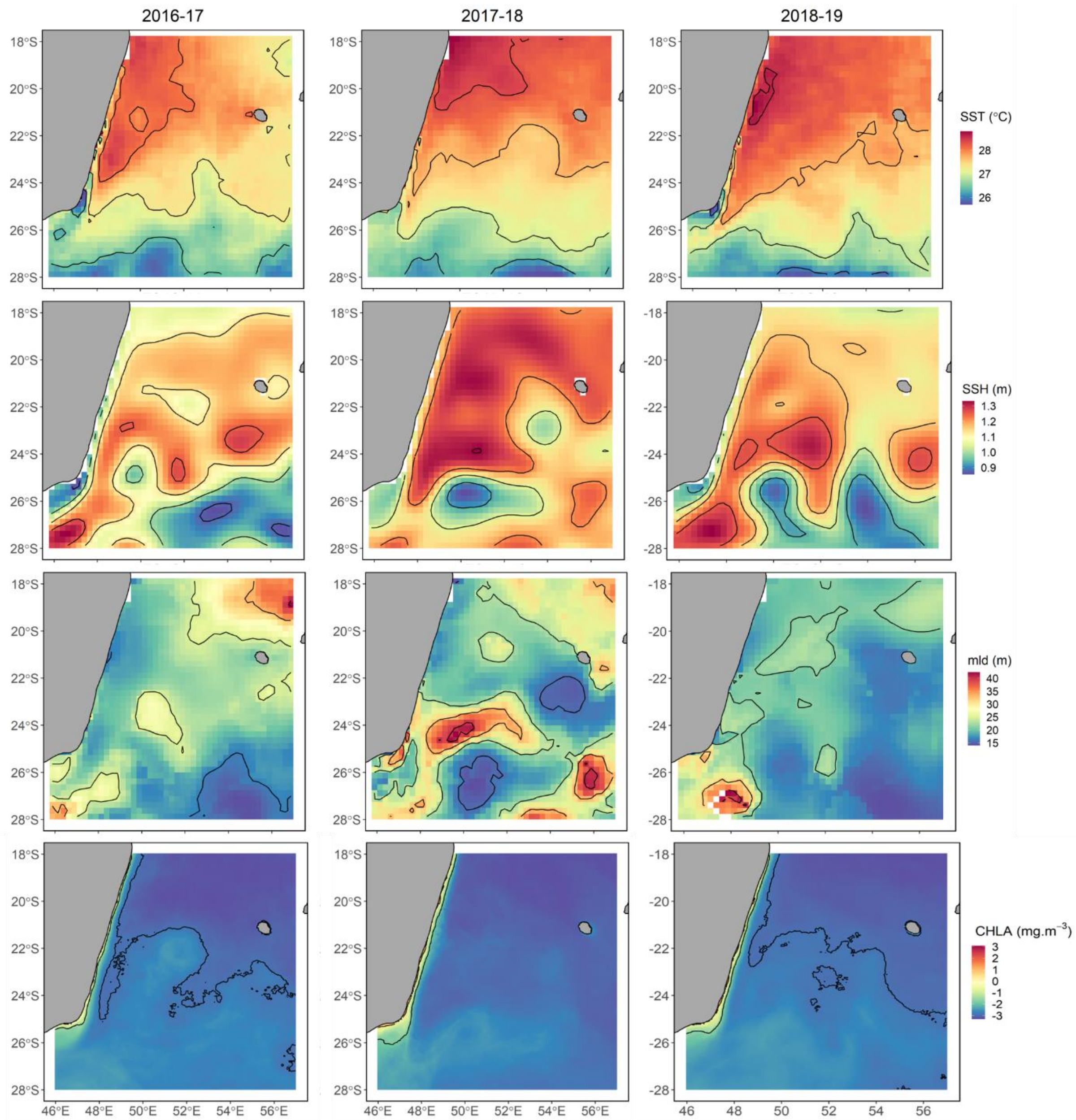

Fig. S14 The seasonal averages for the remote sensing environmental variables, including SST (sea surface temperature), SSH, (sea surface height), mld (mixed layer depth) and CHLA (log chlorophyl a concentration) from top to bottom respectively.

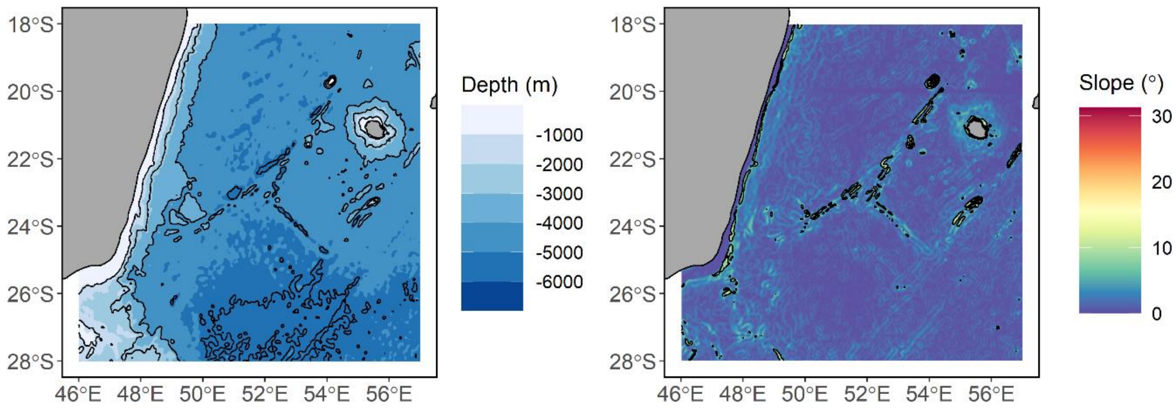

Fig. S15 The depth and bathymentric gradeint (slope) of the oceanic environment surrounding the WTS foraging locations.

Table S1 Details of GPS deployments on Wedge-tailed Shearwaters throughout the study duration.

Data collection period	Breeding season	Breeding stage	Number deployed	GPS models	Waterproofing	Manufacture details	Dimensions (mm)	Mass (g)	Fix rate (min)
10 December 2016 – 27 January 2017	2016/17	Incubation	35	CatTraQ2™	Heat-shrink	Catnip Technologies, USA	44x23x12	10	60
			5	Axy-3™ Axy-Trek	Resin	TechnoSmArt, Rome, Italy	30x22x10	8	60
		Chick rearing	14	CatTraQ2™	Heat-shrink	Catnip Technologies, USA	44x23x12	10	60
			2	Axy-3™ Axy-Trek	Resin	TechnoSmArt, Rome, Italy	30x22x10	8	60
20 November 2017 – 27 December 2017	2017/18	Incubation	20	CatTraQ2™	Heat-shrink	Catnip Technologies, USA	44x23x12	10	10
11 December 2018 – 4 January 2019	2018/19	Incubation	10	CatTraQ2™	Heat-shrink	Catnip Technologies, USA	44x23x12	10	10

Table S2 Classification of GPS tracks from Wedge-Tailed Shearwaters within different breeding stages (stage) and sexes (M = male; F = female; U = unidentified) from Réunion Island. The trip statuses were recorded as 'complete' when the start and end point of a foraging trip were at the colony and 'incomplete' when tracks started/ended near the colony and start/end times could accurately be inferred. The ID refers to the number of individual shearwaters and trip is the number of foraging trips recoded.

Stage	Sex	Trip status	ID	Trips
Incubation	M	Complete	3	3
	M	Incomplete	2	2
	F	Complete	4	8
	F	Incomplete	6	6
	U	Complete	3	3
	U	Incomplete	5	5
Chick rearing	M	Complete	5	18
	M	Incomplete	2	6
	F	Complete	4	20
	F	Incomplete	3	4
	U	Complete	1	6

Table S3 Statistical variables for the Linearised Mixed Models (LMM) testing the effect of breeding stage, sex, and the interaction there of (*) on the foraging trip parameters of Wedge-tailed Shearwaters from Réunion Island.

Term	Estimate	SE	df	t -value	P
Maximum foraging trip distance					
Intercept	488.100	129.600	42.000	3.766	0.001
Stage	-355.400	173.000	21.000	-2.055	0.053
Sex	117.100	158.500	21.000	0.739	0.468
Stage*Sex	-154.500	239.900	21.000	-0.644	0.527
Trip duration					
Intercept	8.687	2.449	42.000	3.548	0.001
Stage	-6.032	3.215	21.000	-1.876	0.075
Sex	2.549	2.989	21.000	0.853	0.403
Stage*Sex	-3.469	4.418	21.000	-0.785	0.441
Distance travelled per day					
Intercept	0.297	0.042	42.000	7.028	0.000
Stage	0.046	0.047	21.000	0.983	0.337
Sex	-0.017	0.049	21.000	-0.351	0.729
Stage*Sex	-0.042	0.057	21.000	-0.725	0.477
Travel speed					
Intercept	2.014	0.297	42.000	6.787	0.000
Stage	0.328	0.326	21.000	1.007	0.326
Sex	-0.008	0.346	21.000	-0.024	0.981
Stage*Sex	-0.407	0.395	21.000	-1.030	0.315
Foraging trip length					
Intercept	1517.000	433.900	42.000	3.498	0.001
Stage	-1060.000	573.600	21.000	-1.848	0.079
Sex	394.600	530.100	21.000	0.744	0.465
Stage*Sex	-547.100	791.600	21.000	-0.691	0.497

Table S4 Model selection for Generalized Additive Mixed Models assessing the response of Wedge-tailed Shearwaters' foraging probability to environmental models. The environmental variables include bathymetry (bathy), chlorophyll a concentration (CHLA), mixed layer depth (MLD), bathymetric gradient (slope), sea surface height anomalies (SSHA), and sea surface temperature (SST). The most parsimonious (ΔAICc ≤ 2) and null models are presented. Environmental variables included are indicated by "+" and significant variables are in bold ($P < 0.05$).

Intercept	Bathy	CHLA	MLD	Slope	SSHA	SST	df	logLik	AICc	ΔAICc	Weight
Incubation											
-0.02	**+**	**+**	**+**		**+**	**+**	43	-3619.30	7325.80	0.00	0.46
-0.02	**+**	**+**	**+**	+	**+**	**+**	45	-3616.77	7326.28	0.48	0.36
-0.01							0	-3851.67	7705.34	379.53	0.00
Chick rearing											
0.02	**+**	**+**	**+**		**+**		32.00	-1590.10	3245.49	0.00	0.36
0.02	**+**	**+**	**+**		**+**	+	33.00	-1589.07	3245.64	0.15	0.33
0.02	**+**	**+**	**+**	+	**+**		33.00	-1589.78	3246.97	1.48	0.17
0.02	**+**	**+**	**+**	+	**+**	+	34.00	-1588.92	3247.39	1.91	0.14
-0.03							1	-1717.26	3436.53	191.04	0.00
Long foraging trips											
0.25	**+**	**+**	**+**	+	**+**		28	-671.19	1401.23	0.00	0.61
0.23	**+**	**+**	**+**	+	**+**	+	29	-671.15	1403.10	1.86	0.24
0.02							1	-779.75	1561.51	160.28	0.00
Short foraging trips											
-0.08	**+**	**+**	**+**	**+**	+	**+**	33	-827.83	1725.30	0.00	0.49
-0.09	**+**	**+**	**+**	**+**		**+**	31	-830.52	1725.38	0.08	0.47
-0.08							0	-936.87	1875.74	150.44	0.00

Table S5 Summery statistics of the significant environmental variables included in the Generalized Additive Mixed Models assessing the response of Wedge-tailed Shearwaters' foraging probability to environmental models. The environmental variables include bathymetry (bathy), chlorophyll a concentration (CHLA), mixed layer depth (MLD), bathymetric gradient (slope), sea surface height anomalies (SSHA), and sea surface temperature (SST). Environmental variables were smoothed with cubic regression splines to avoid overfitting the models and bird ID was added as random effects. To deal with spatial inherent structure in the tracking data, longitude and latitude were included as a covariate as smoothed interaction terms.

	df	X_2	P
Incubation			
BATHY	4	39.690	0.000
log(CHLA)	8	40.580	0.000
SST	3	29.480	0.000
SSHA	2	6.830	0.035
MLD	4	21.180	0.001
Chick rearing			
BATHY	4	39.690	0.000
log(CHLA)	8	40.580	0.000
SST	3	29.480	0.000
SSHA	2	6.830	0.035
MLD	4	21.180	0.001
Long foraging trips – chick rearing			
BATHY	3	15.410	0.005
log(CHLA)	7	48.730	0.000
SSHA	3	15.140	0.005
MLD	3	26.800	0.000
Short foraging trips – chick rearing			
BATHY	4	26.452	0.000
log(CHLA)	8	47.842	0.000
SST	3	9.783	0.023
sqrt(slope)	3	10.404	0.018
MLD	4	37.958	0.000

References

Garriga J, Palmer JR, Oltra A, Bartumeus F (2016) Expectation-maximization binary clustering for behavioural annotation. PLoS ONE 11: e0151984.

Lascelles BG, Taylor P, Miller M, Dias M, Oppel S, Torres L, Hedd A, Le Corre M, Phillips R, Shaffer SA (2016) Applying global criteria to tracking data to define important areas for marine conservation. Diversity and Distributions 22: 422-431