The following supplement accompanies the article

Sexual segregation in a wide-ranging marine predator is a consequence of habitat selection

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Extra Methodological Details

Details on GPS and TDR tracked birds

Table S1. The number of northern gannets sampled each year during the study. The number of unique individuals sampled is reported as many individuals were sampled across multiple years. Time Depth Recorders (TDRs) were not deployed in 2010.

Year	GPS			TDR		
	Males (n)	Females (n)	Total (n)	Males (n)	Females (n)	Total (n)
2010	23	26	49	NA	NA	NA
2011	15	10	25	13	6	19
2012	15	18	33	5	8	13
Total No. unique individuals sampled	25	30	55	14	10	24

Using Bhattacharyya's affinity (BA) and randomization to test for overlap

Using BA as a measure of spatial overlap, we used a randomization technique to test the null hypothesis that there was no difference in the spatial distribution of males and females in each year of the study. If the null hypothesis was true, the magnitude of the overlap between males and female 50% and 95% kernels should not differ significantly from that calculated if sex were randomly assigned. Therefore, for each year the sex of each bird was randomly assigned using the same sex ratio as the observations in that year. In total, we generated a null distribution for BA based on 1000 randomizations of our dataset in order to test whether the overlap between male and female home-ranges was significantly different than expected. P-values were determined by the proportion of random overlaps that were smaller than the observed overlap, if the observed overlap was smaller than all 1000 randomly generated overlaps, then p was ≤ 0.005 (see Breed et al. 2006 for a similar approach). More details on BA and other measures of spatial overlap can be found in Fieberg & Kochanny (2005).

Extra information on stable isotope analysis

Isotope analysis was conducted at the Natural Environment Research Council (NERC) Life Sciences Mass Spectrometry Facility in East Kilbride, UK. Before analysis, blood samples were dried in a drying oven before being ground into a fine powder. Approximately 0.7 mg (± 0.1 mg) of each tissue was weighed into a tin capsule, combusted and oxidized in a Costech ECS 4010 elemental analyser, with the respective isotope ratios of carbon and nitrogen of the CO_2 and N_2 gas output measured by a Thermo Electron Delta Plus XP mass spectrometer. Three internal laboratory standards were analysed for every ten unknown samples, and measurement precision of both $\delta^{15}N$ and $\delta^{13}C$ was estimated to be ≤ 0.2‰. Internal standards are routinely (once a month) calibrated against International Atomic Energy Agency and National Institute of Standards and Technology stable isotope reference materials.

Isotope ratios (R) of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ are expressed in delta (δ) units, as parts per thousand (‰) difference from an international standard, where: $\delta^{13}C$ or $\delta^{15}N$ = [(R sample/ R standard) – 1] × 1000. The international standards (=0‰) for stable isotope analysis are atmospheric N_2 (air) for nitrogen and Pee Dee Belemnite (V-PDB) for carbon.

In general, $\delta^{15}N$ increases by 3 to 5 ‰ with each trophic level (DeNiro & Epstein 1981, Hobson & Clark 1992, Bearhop et al. 2002). Although $\delta^{13}C$ also increases with trophic level, the main causes of variation in $\delta^{13}C$ are differences in photosynthetic biochemistry within and among marine primary producer communities. Therefore, in marine ecosystems, $\delta^{13}C$ signatures are typically used to infer the origin of food from $\delta^{13}C$ gradients that exist between water masses, as well as gradients between inshore/ offshore waters and benthic/ pelagic habitat (Hobson et al. 1994, Bearhop 2000, Cherel et al. 2006).

Bayesian Analysis

Trip duration, total distance travelled during a trip and time spent at the colony between trips were modelled using a Bayesian linear mixed effects model (BLMM) with sex and year and their two-way interaction included as covariates and bird identity included as a random intercept. In each model we included non-informative priors for each of the parameters in the model based on recommendations in MCMCglmm manuals (Hadfield 2010). In particular, we used extended priors for the variance of the random intercept included within each model. A variety of different specification priors was tested to ensure that the results were not influenced by our initial choice of prior. A similar approach to prior specification was used when modelling the multi-variate model for the multivariate stable isotope analysis. Following recommended protocols (Hadfield 2010), we fitted heterogeneous variance components across traits, allowing the between individual variance to differ between $\delta^{15}N$ and $\delta^{13}C$ as well as estimating the covariance between them. We also allowed the estimated residual variance to differ between $\delta^{15}N$ and $\delta^{13}C$

Once a suitable prior had been chosen we ran three separate MCMC chains for 30 000 iterations, with a burn-in of 10 000 and a thinning interval of 10. These values were chosen on the basis that they gave us a model in which the effective sample size for the estimate of each parameter was 2000 or greater. Each chain was tested for auto-correlation,, to ensure that it had converged we used the Gelman-Rubin diagnostic (Gelman & Rubin 1992). We used posterior predictive checks - which compare the predicted distribution to the observed data – to ensure that our models provided an adequate fit to the data (Congdon 2010).

Figure S1. Plots of male and female tracks in each year. Tracks are plotted with unique colours for each individual tracked.

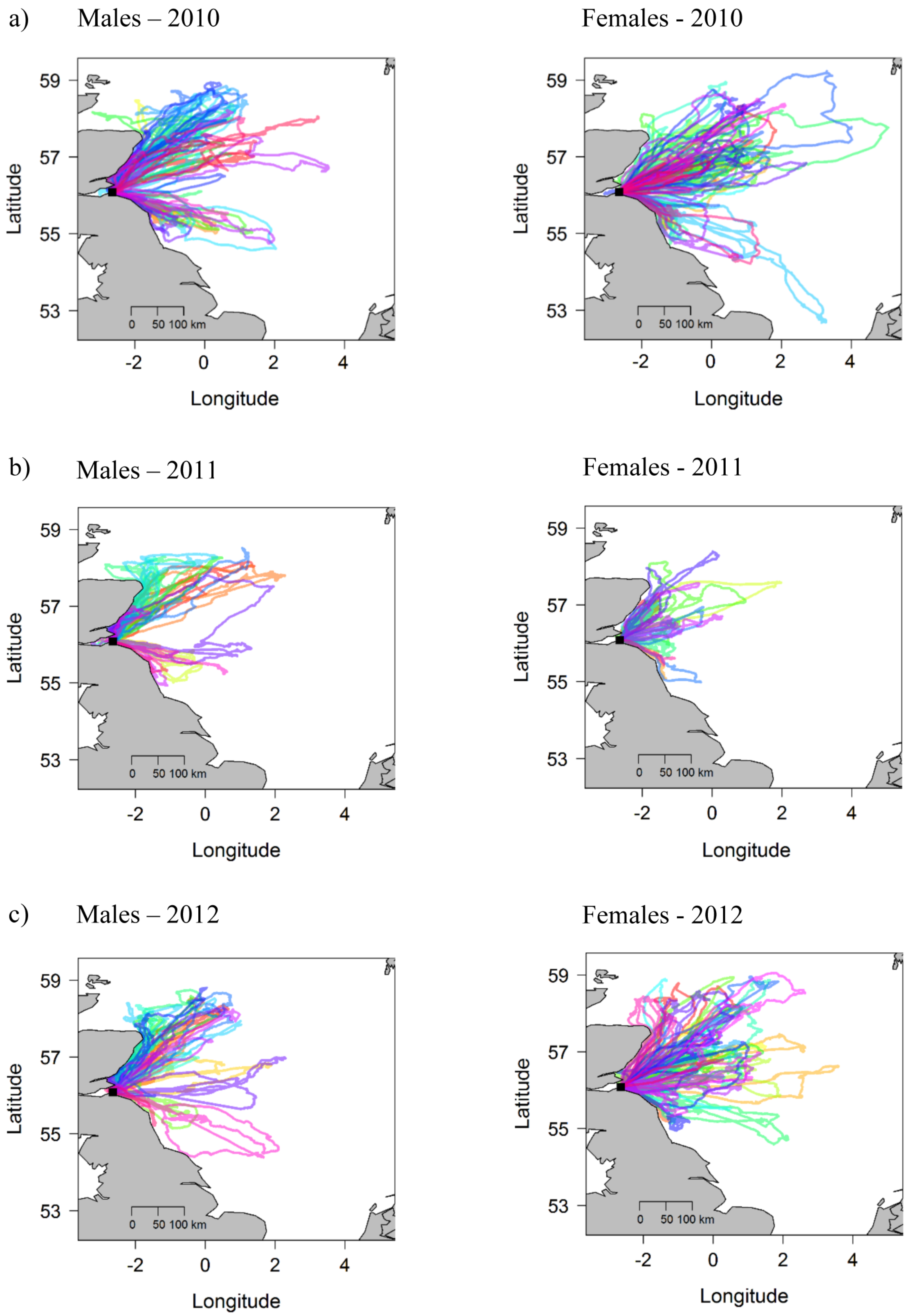
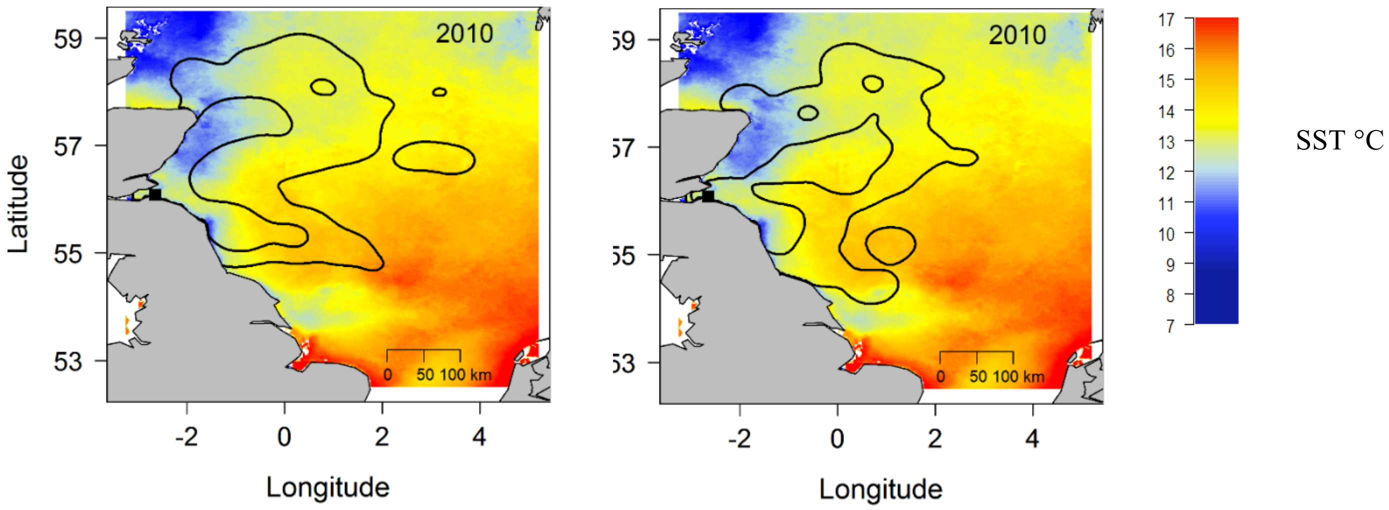
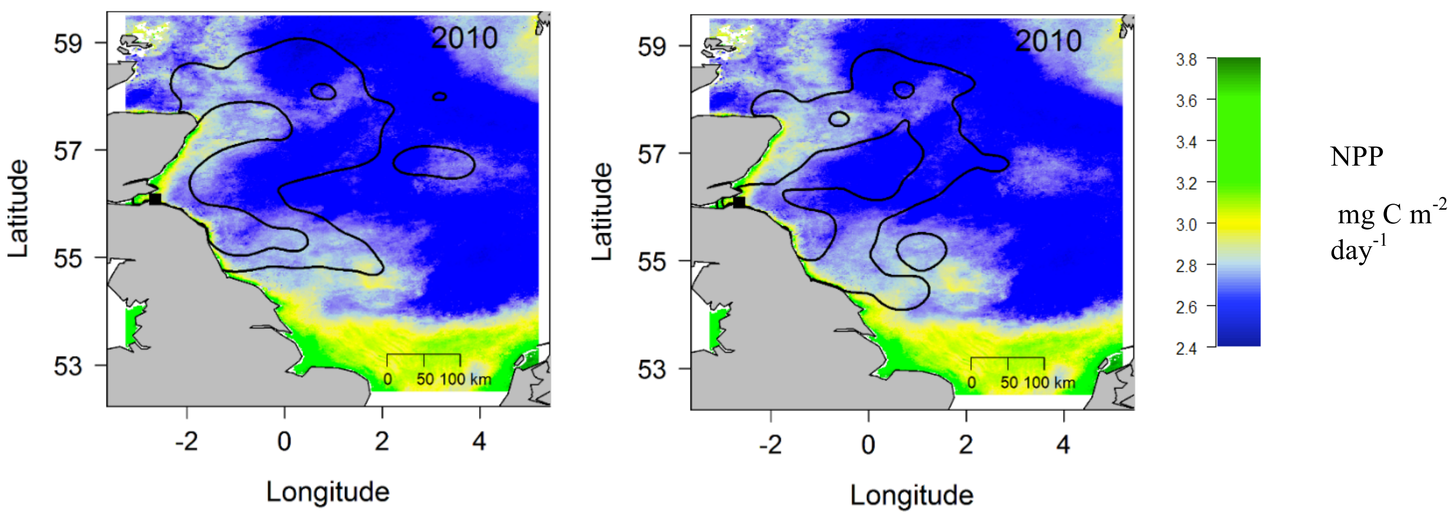


Figure S2. Plots of averaged environmental variables overlaid with male and female 50% and 95% home ranges based on GPS tracking data for a) 2010, b) 2011 and c) 2012.

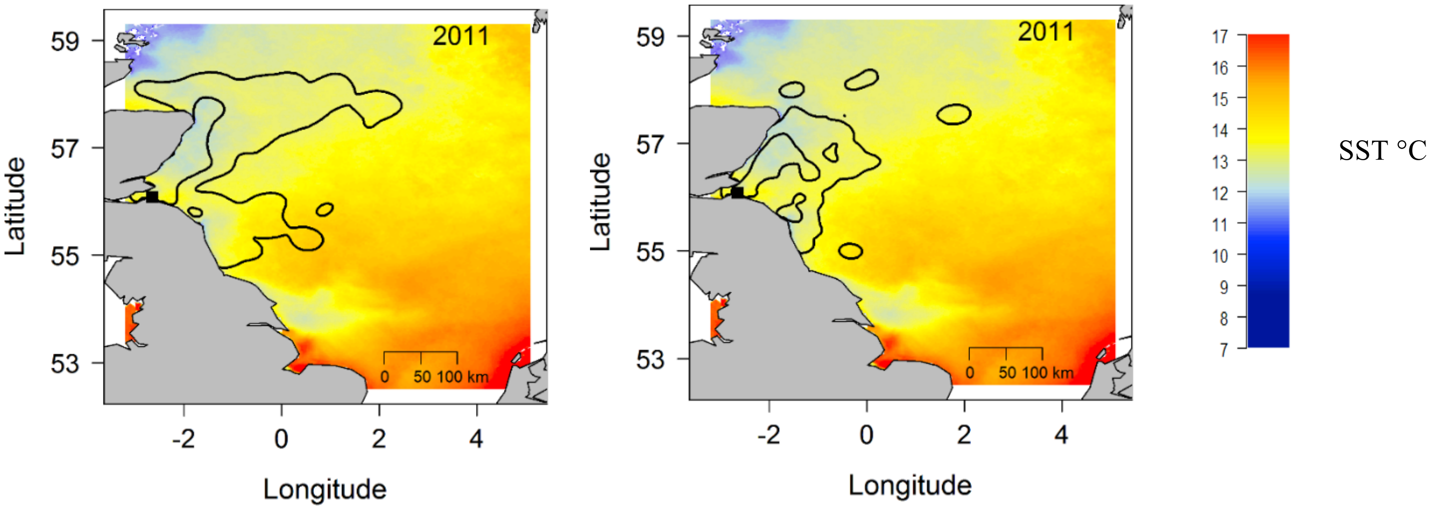
SST °C - 2010



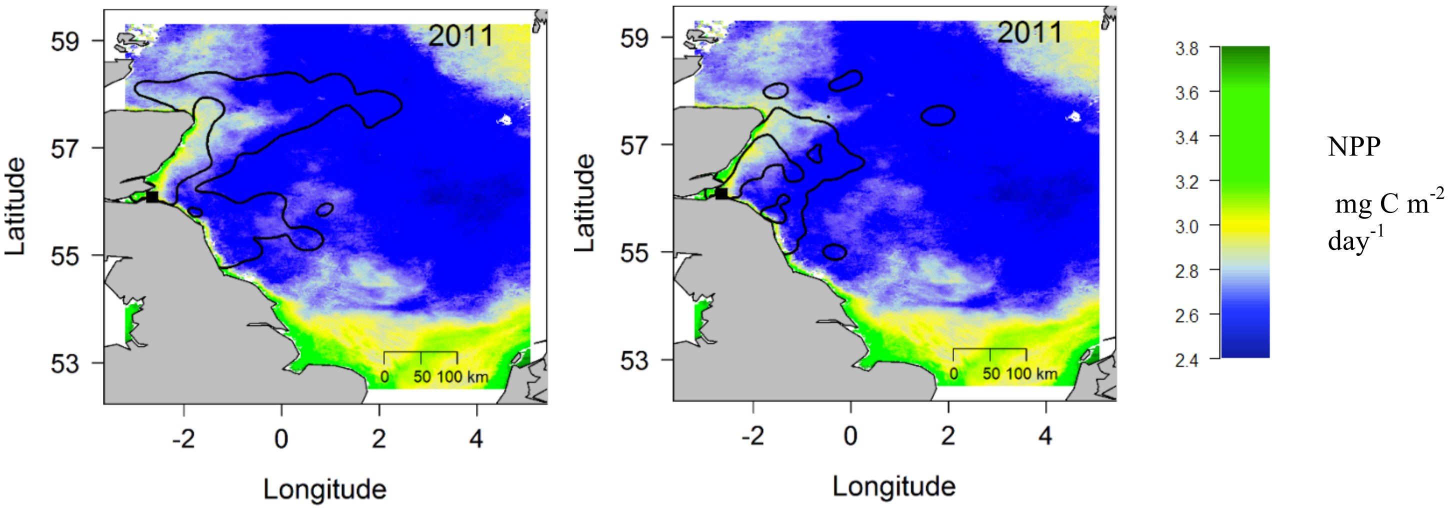
NPP, mg C m^{-2} day^{-1} - 2010



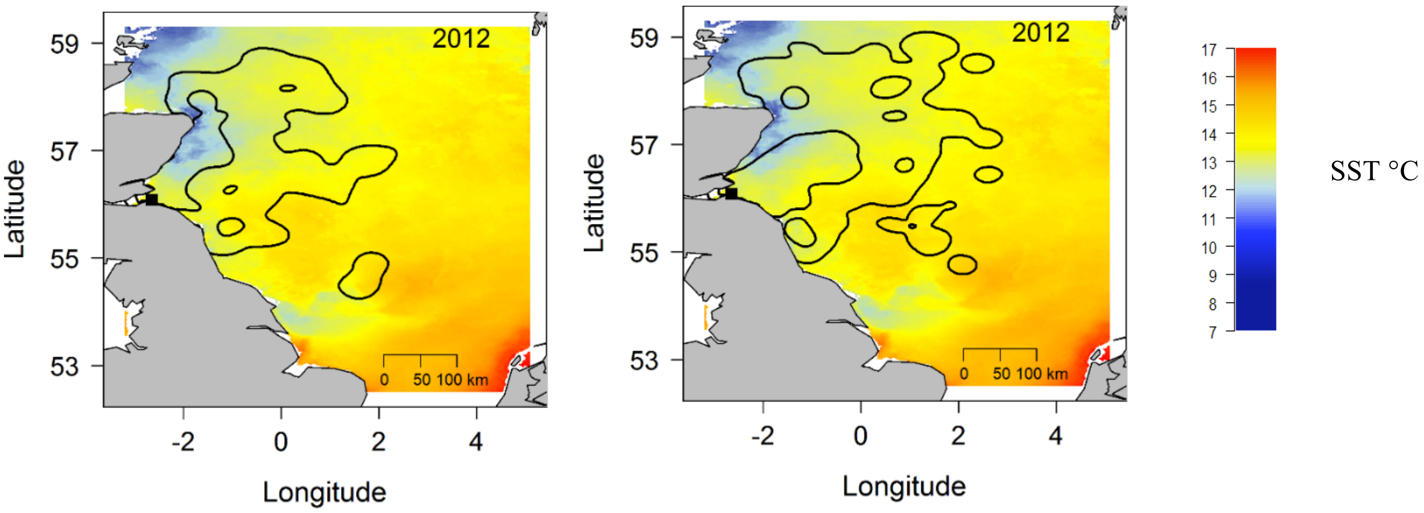
SST °C - 2011



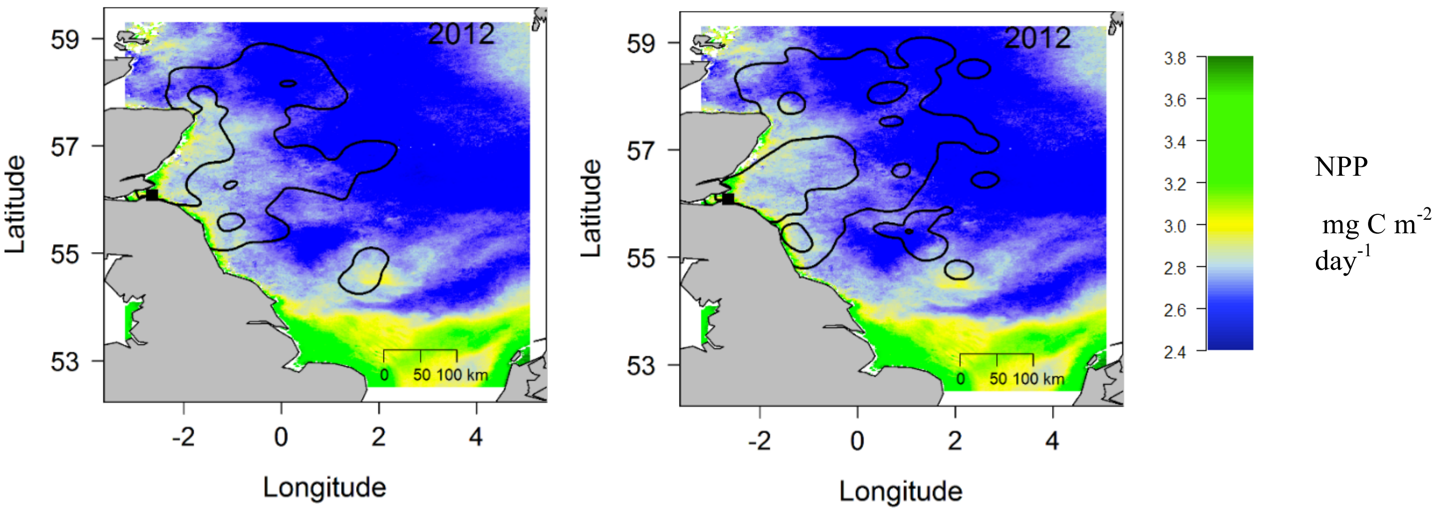
NPP, mg C m^{-2} day^{-1} - 2011



SST °C - 2012



NPP, mg C m^{-2} day^{-1} - 2012



Generalized Additive Mixed model (GAMM) analysis

When modelling the Habitat Selection Functions (HSF) we used GAMMs to estimate smoothers for each of the environmental parameters. As part of the gam functions within the R package mgcv (Wood 2006) the smoothing parameter is chosen automatically using generalised cross-validation (GCV). In order to model spatial auto-correlation we included an isotropic thin plate spline which is set up as a two-dimensional smoother based on both x and y coordinates (in R this would be specified as s(x,y)). Incorporating a spatial smoother is one means of modelling a spatial trend within a model, more details on this approach can be found in Wood (2003) and Bivand et al. (2008). The coordinates used when modelling a spatial smoother were projected in a UTM (Universal Transverse Mercator) projection rather than in longitudes and latitudes. This was done because longitude and latitudes a projected onto a spherical surface which can influence how the distance between points is measured. Spatial plots from the GAMM models were re-projected back into longitude and latitudes for plotting purposes. Prior to modelling we examined correlations between all environmental variables in order to ascertain whether collinearity may have occurred. We assumed that a correlation of greater than $\boldsymbol{r_s}$ 0.4 was problematic, but all correlations between the different environmental variables were lesser than 0.4. However, distance from the colony was not incorporated within these models as it was strongly correlated with different environmental variables. However, including a spatial smoother allows us to model how usage changes with distance from the colony. Initially we restricted GAMMs to a maximum of 5 knots to prevent over-fitting, however if GAMMs failed diagnostic checks we increased the number of knots until these checks were satisfactory. For the spatial smoothers in the models we used the default settings in the mgcv package (Wood 2006) to estimate the number of knots required.

When performing GAMMs, minimum adequate models were selected by backwards selection, using *K*-fold cross-validation, where $K = 5$. Following Hastie et al. (2001) the *K*-fold cross-validation statistic for prediction error (KCV) is calculated as:

$$KCV = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - \hat{y}^{-K(i)}\right)^2 \quad ,$$

where y_i represents the *i*th observation, $\hat{y}_i$ is the predicted value, n is the number of observations and *K* represents the *K*th fold. Under this approach models with smaller KCV values are preferred. We used KCV values to compare models in which the sex-specific smoother for each environmental variable was replaced by (1) a single smoother estimated for both sexes; (2) an interaction between sex and the environmental variable; (3) a main effect for each environmental variable and (4) removal of the environmental variable altogether. Cross-validation is a conservative approach to model selection; however, we adopted it here because the inherent spatial and temporal auto-correlation within tracking datasets can lead to over-parameterized models if information criteria, such as AIC, are used for model selection. In addition, all smooths were produced using cubic regression splines with shrinkage, which allows variables to be penalized out of the model during fitting (Wood 2006), to reduce the risk of over-parameterization.

The importance of random effects was assessed by comparing model KCV values between models in which the random effect was included and models in which it was removed.

TDR Dive Data

TDRs were set up to record once dive depth > 1.5m, therefore they did not record data for the shallowest dives. The descent gradient of each dive was calculated and smoothed using LOWESS (Locally Weighted Scatterplot Smoothing) smoother with f = 1/8. Dive data from the TDR loggers was then partitioned into phases according to two sets of criteria:

PHASE 1

D = Plunge dive phase, from start of dive last point when smoothed gradient >1.8 m/s.

B = Bottom phase, from last descent point to last point when smoothed gradient ≥ -0.35 m/s.

A = Ascent phase - from last bottom point to end of dive.

PHASE 2

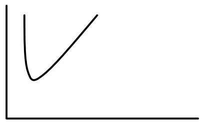
D = Overall dive phase, from start of dive to the first point where depth = maximum dive depth.

A = Overall ascent phase – remainder of dive.

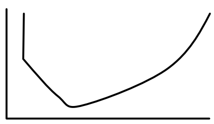
This procedure gave us a wide range of trip metrics including maximum depth attained and length of the bottom phase of the dive which allowed us to assign dives as either V-shaped or U-shaped. Dives were classified as U-shaped dives if the bottom time exceeded 2.7 seconds based on data from Garthe et al. (2000). Examples of typical dives are displayed below.

Figure S3. Characteristics of U and V shaped dives during the study.

V - Steep-dive, followed by uninterrupted ascent. Bottom time ≤ 2.7 s



U - Steep-dive followed by appreciable further foot-propelled descent. Bottom time > 2.7 s



Model Tables and Figures

Table S2. Results from a Bayesian Linear Mixed Model (LMM) showing the differences in the behaviour of males and females, There was no evidence of a sex × year interaction in any model. Sample size for Trip Duration and Trip Length n = 493 trips/55 birds; for Time at Colony n = 379 trips /52 birds

	Model											
	Trip Duration (hrs)				Trip Length (km)				Time at Colony Between Trips (Hrs)			
Variable	□	Lower 95% CI	Upper 95% CI	*p*-value	□	Lower 95% CI	Upper 95% CI	*p*-value	□	Lower 95% CI	Upper 95% CI	*p*-value
Intercept	25.34	23.27	27.41	<0.001	552.15	500.61	600.66	<0.001	1.72	1.46	1.96	<0.001
Sex (M)	-2.63	-4.91	-0.53	0.020	-50.52	-108.13	10.63	0.10	0.04	-0.24	0.32	0.76
Year (2011)	-2.78	-5.56	-0.14	0.048	-126.06	-188.81	-67.05	<0.001	0.15	-0.18	0.48	0.39
Year (2012)	-1.57	-4.09	1.14	0.23	-19.16	-71.84	38.45	0.49	0.12	-0.18	0.41	0.43

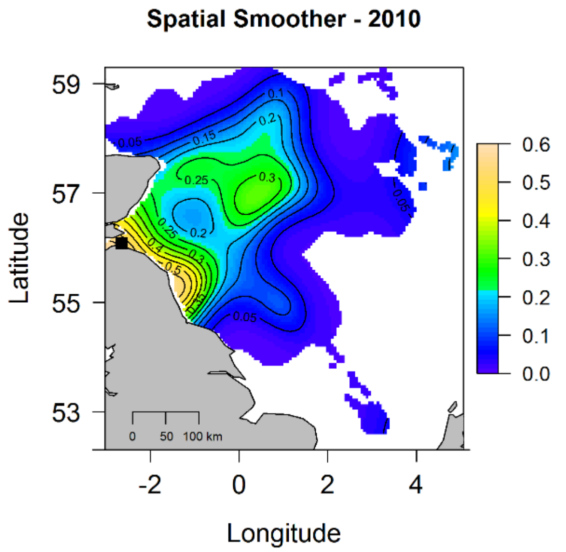
Table S3. Summary of covariates included in the best fitting habitat selection function GAMM in each year of the study. The sample size reported for each year is the combined number of observations and randomly generated pseudo-absences. Here, s represents a smooth function and edf is the estimated degrees of freedom for the smoother.

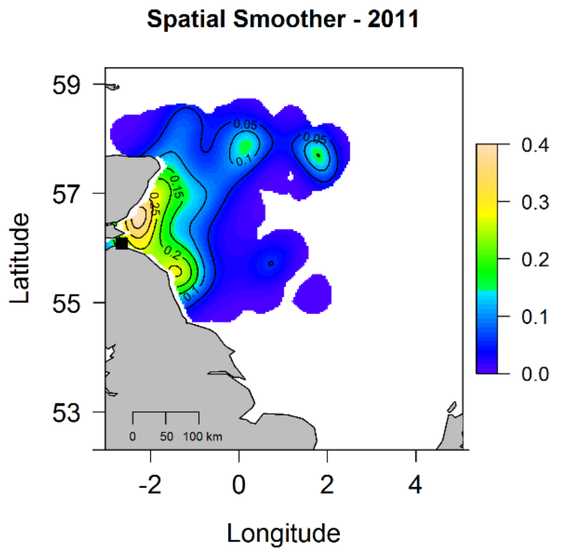
Year	Variable	Smoother edf/ p value
2010 (n = 166780)		
	s(NPP, Sex = Females)	3.50, p = < 0.001
	s(NPP, Sex= Males)	3.75, p = < 0.001
	s(SST, Sex = Females)	3.12, p = < 0.001
	s(SST, Sex = Males)	3.35, p = < 0.001
	s(Longitude, Latitude)	21.44, p < 0.001
	Random Intercept for Bird ID	$□^2$ = 0.067
2011 (n = 137847)		
	s(NPP, Sex = Females)	3.99, p < 0.001
	s(NPP, Sex = Males)	3.37, p < 0.001
	s(SST, Sex = Females)	4.96, p < 0.001
	s(SST, Sex = Males)	4.52, p < 0.001
	s(Longitude, Latitude)	20.18, p < 0.001
	Random Intercept for Bird ID	$□^2$ = 0.12
2012 (n = 195404)		
	s(NPP, Sex = Females)	4.77, p < 0.001
	s(NPP, Sex = Males)	4.53, p <0.001
	s(SST, Sex = Females)	4.31, p <0.001
	s(SST, Sex = Males	4.72, p <0.001
	s(Longitude, Latitude)	22.54, p <0.001
	Random Intercept for Bird ID	$□^2$ = 0.044

Table S4. Model selection for GAMM habitat selection functions in each year. The □ KCV scores gives the change in model KCV score when the term in question replaced the term chosen in the best fitting model. Terms chosen in the best fitting in model are highlighted in bold and have a □ KCV score of 0.

Year	Variable	□ KCV score
2010		
	s(NPP, by= Sex)	**0**
	s(NPP)	+6
	NPP: Sex	+ 5
	NPP	+7
	NPP Removed	+48
	s(SST, by= Sex)	**0**
	s(SST)	+10
	SST: Sex	+12
	SST	+12
	SST Removed	+ 59
	s(Longitude, Latitude)	**0**
	s(Longitude, Latitude) removed	+575
	Random Intercept for Bird ID	**0**
	Random Intercept for Bird ID Removed	+76
2011		
	s(NPP, by= Sex)	**0**
	s(NPP)	+18
	NPP: Sex	+15
	NPP	+13
	NPP Removed	+41
	s(SST, by= Sex)	**0**
	s(SST)	+25
	SST: Sex	+23
	SST	+43
	SST Removed	+45
	s(Longitude, Latitude)	**0**
	s(Longitude, Latitude) removed	+444
	Random Intercept for Bird ID	**0**
	Random Intercept for Bird ID Removed	+52
2012		
	s(NPP, by= Sex)	**0**
	s(NPP)	+5
	NPP: Sex	+5
	NPP	+6
	NPP Removed	+45
	s(SST, by= Sex)	**0**
	s(SST)	+40
	SST: Sex	+45
	SST	+42
	SST Removed	+53
	s(Longitude, Latitude)	**0**
	s(Longitude, Latitude) removed	+747
	Random Intercept for Bird ID	**0**
	Random Intercept for Bird ID Removed	+20

Figure S4. Plots of the spatial smoothers from the HSF in each year of the study. Predictions from the model are plotted on the response scale and show predicted usage. The location of Bass Rock is displayed as a black square.





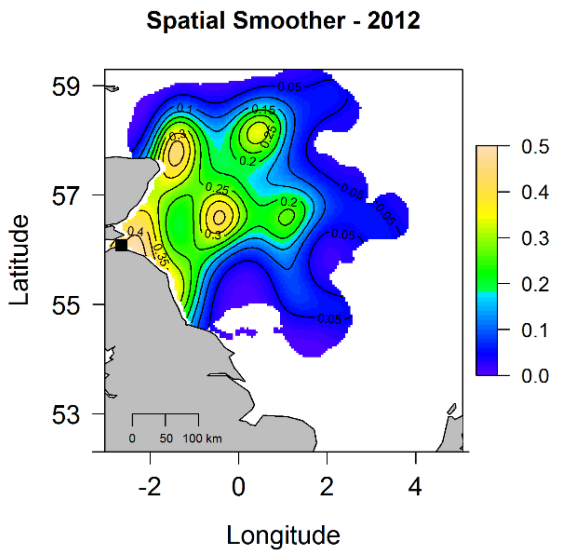


Table S5. Results from the GAMM modelling the probability that a dive will be classed as a U-shaped dive rather than a V-shaped dive. N = 6310/ 127 trips, 23 birds. Where s() denotes the variables was fitted as a smoother and edf = estimated degrees of freedom.

Variable	□	Lower 95% CI	Upper 95% CI	p-value
Intercept (Female)	-1.62	-1.99	-1.25	<0.001
Sex (Male)	0.92	0.35	1.48	0.0012
Mass	-0.024	-0.29	0.25	0.90
Smoothers				
s(Time of Day)	edf = 5.13	p = <0.001		
s(Lon, Lat)	edf = 22.16	p = <0.001		
Random Effects				
Bird ID	$□^2$ = 0.11			
Trip ID	$□^2$ = 0.86			

Table S6. Model selection table for the Binomial GAMM for Dive Type (Probability of dive being class as U-shaped). Variables retained in final model denoted in bold.

Variable	Model Formula	□ KCV Score
Body Mass	s(Body Mass, by=Sex)	+17
	s(Body Mass)	+8
	Body Mass × Sex	+14
	Body Mass	+8
	Body Mass removed	**0**
Time of Day	s(Time of Day, by=Sex)	+17
	s(Time of Day)	**0**
	Time of Day × Sex	+85
	Time of Day	+80
	Time of Day removed	+72
Sex	Sex	
	Sex removed	
Spatial Smoother	**s(Longitude, Latitude)**	**0**
	Spatial Smoother removed	+ 87
Random Intercept for Bird ID	**Random Intercept included**	**0**
	Random Intercept removed	+243
Random Intercept for trip ID	**Random Intercept included**	**0**
	Random Intercept removed	+329
Temporal Auto-correlation	Temporal Auto-correlation included	+2
	Temporal Auto-correlation removed	**0**

Figure S5. GAMM smoother showing the relationship between time of day and the probability of a dive being classed as U-shaped.

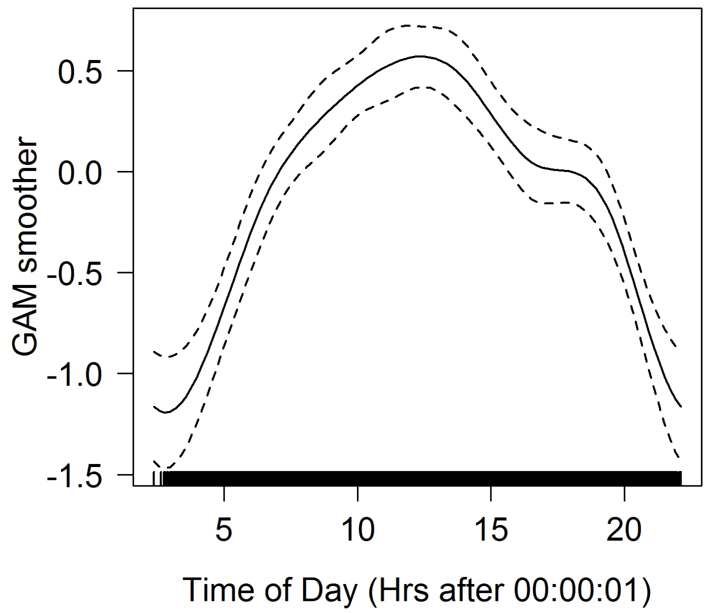


Table S7. Results from the model of maximum depth reached during V-shaped dives. N = 4274 dives/ 125 trips, 23 birds.

Variable	□	Lower 95% CI	Upper 95% CI	p-value
Intercept (F)	5.57	5.08	6.06	<0.001
Sex (M)	-0.81	-1.55	-0.11	0.021
Mass	0.52	0.13	0.91	0.018
Smoothers				
s(Time of Day)	edf = 4.10	p = <0.001		
s(Lon, Lat)	edf = 22.16	p = <0.001		
Random Effects				
Bird ID	□^{2} = 0.21			
Trip ID	□^{2} = 0.87			

Table S8. Model selection table for the GAMM of V-Dive depth. Variables included in final model denoted in bold.

Variable	Model Formula	□ KCV Score
Body Mass	s(Body Mass, by=Sex)	+11
	s(Body Mass)	+9
	Body Mass × Sex	+7
	Body Mass	**0**
	Body Mass removed	+13
Time of Day	s(Time of Day, by=Sex)	+2
	s(Time of Day)	**0**
	Time of Day × Sex	+274
	Time of Day	+265
	Time of Day removed	+256
Sex	Sex	
	Sex removed	
Spatial Smoother	**s(Longitude, Latitude)**	**0**
	Spatial Smoother removed	+ 113
Random Intercept for Bird ID	**Random Intercept included**	**0**
	Random Intercept removed	+434
Random Intercept for trip ID	**Random Intercept included**	**0**
	Random Intercept removed	+560
Temporal Auto-correlation	Temporal Auto-correlation included	+3
	Temporal Auto-correlation removed	**0**

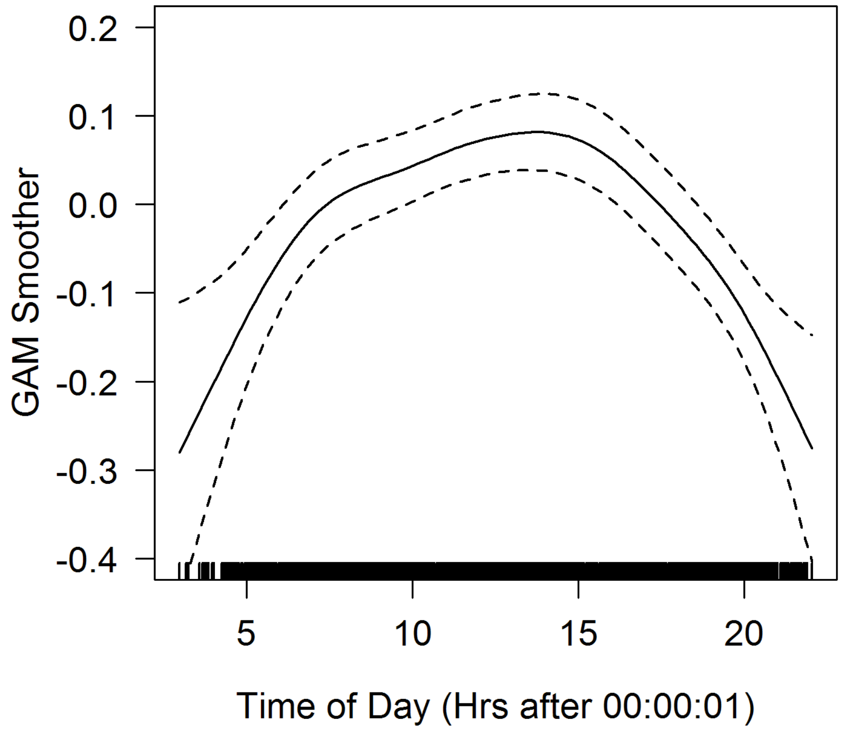
Table S9. Results from the model of maximum depth of U-shaped dives. N = 2036 dives/ 110 trips, 23 birds.

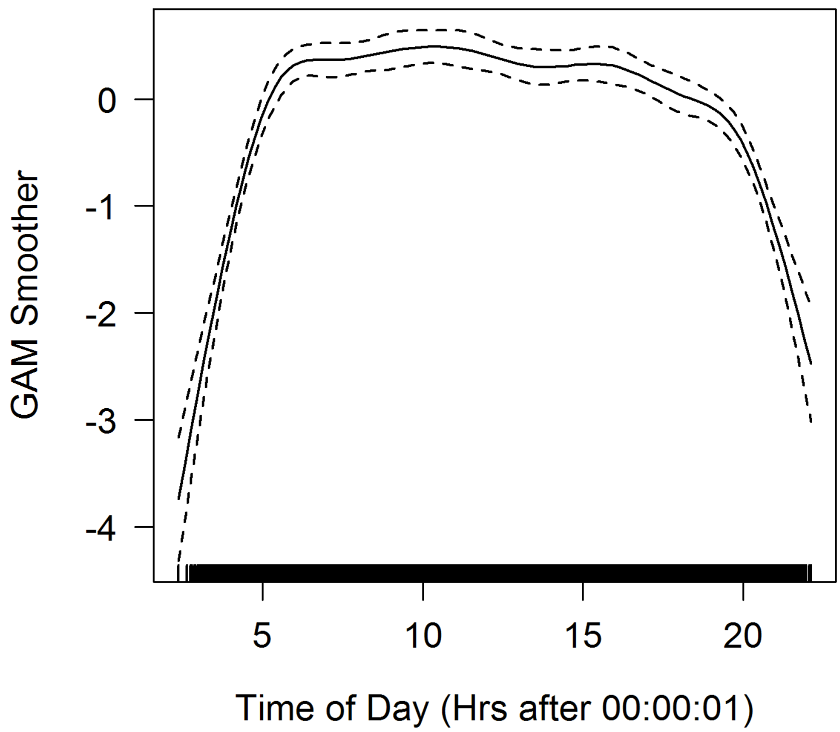
Variable	β	Lower 95% CI	Upper 95% CI	p-value
Intercept (F)	6.19	5.17	7.21	< 0.001
Sex (M)	0.93	-0.52	2.34	0.18
Mass	0.43	-0.31	1.17	0.40
Smoothers				
s(Time of Day)	edf = 3.27	p = <0.001		
s(Lon, Lat)	edf = 21.07	p = <0.001		
Random Effects				
Bird ID	$\sigma^2 = 0.70$			
Trip ID	$\sigma^2 = 1.66$			

Table S10. Model selection table for the GAMM of Maximum Depth reached during U-shaped dives. Variables retained within the final model denoted in bold.

Variable	Model Formula	Δ KCV Score
Body Mass	s(Body Mass, by=Sex)	+9
	s(Body Mass)	+7
	Body Mass × Sex	+7
	Body Mass	+5
	Body Mass removed	**0**
Time of Day	s(Time of Day, by=Sex)	+6
	s(Time of Day)	**0**
	Time of Day × Sex	+38
	Time of Day	+20
	Time of Day removed	+8
Sex	Sex	
	Sex removed	
Spatial Smoother	**s(Longitude, Latitude)**	**0**
	Spatial Smoother removed	+ 162
Random Intercept for Bird ID	**Random Intercept included**	**0**
	Random Intercept removed	+74
Random Intercept for trip ID	**Random Intercept included**	**0**
	Random Intercept removed	+134
Temporal Auto-correlation	Temporal Auto-correlation included	+5
	Temporal Auto-correlation removed	**0**

Figure S6. GAMM smoothers showing the effect of Time of Day on the maximum depth of both a) V-Shaped dives and b) U-shaped dives.





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