Supplement to Tickler et al. (2023) – Mar Ecol Prog Ser 717: 85–105 – https://doi.org/10.3354/meps14376

S1. Supplementary tables and figures

Supplementary tables

Table S1: Depth bin boundaries, in metres, for depth histograms transmitted by tags

Tag	ID	Bin1	Bin2	Bin3	Bin4	Bin5	Bin6	Bin7	Bin8	Bin9	Bin10	Bin11	Bin12
1	391300800	5	10	25	50	75	100	150	200	250	300	500	>500
2	391301000	5	10	25	50	75	100	150	200	250	300	500	>500
3	391301400	5	10	25	50	75	100	150	200	250	300	500	>500
4	391303300	5	10	25	50	75	100	150	200	250	300	500	>500
5	391400800	5	10	25	50	75	100	125	150	200	250	300	2000
6	391401600	5	10	25	50	75	100	125	150	200	250	300	2000
7	391401800	5	10	25	50	75	100	125	150	200	250	300	2000

Table S1: Upper bin boundaries for temperature histograms transmitted by tags (in degrees centigrade)

Tag	TOPID	Bin1	Bin2	Bin3	Bin4	Bin5	Bin6	Bin7	Bin8	Bin9	Bin10	Bin11	Bin12
1	391300800	5	10	14	18	20	22	24	26	28	30	32	>32
2	391301000	5	10	14	18	20	22	24	26	28	30	32	>32
3	391301400	5	10	14	18	20	22	24	26	28	30	32	>32
4	391303300	5	10	14	18	20	22	24	26	28	30	32	>32
5	391400800	18	20	22	23	24	25	26	27	28	29	30	45
6	391401600	18	20	22	23	24	25	26	27	28	29	30	45
7	391401800	18	20	22	23	24	25	26	27	28	29	30	45

Table S3: Variance inflation factors for the fixed effects tested in a GLMM on the five tags with semi-diel depth data.

Variable	GVIF^a	DF	GVIF^(1/2Df)^b
TOD	1.00	1	1.00
SST	1.01	1	1.01
Moon	1.01	3	1.00
MLD	1.01	1	1.01
TL	1.02	1	1.01

a. GVIF is the Generalised Variance Inflation Factor (Fox & Monette 1992)

b. GVIF adjusted to account for degrees of freedom of predictors

Table S4: Results of Tukey's test of honestly significant difference of group means for an analysis of variance of shark daily depth by calendar month, based on pooled depth data from seven individuals. Adjusted p values account for multiple pairwise comparisons, with bold values indicating significant difference in group means at the 5% level.

Group1	Group2	Group2 depth – Group1 depth (m)			Adjusted p
		Estimate	UCL	LCL	value
Feb	Mar	-6.31	-13.1	0.503	0.090
Feb	Apr	-10.9	-17.4	-4.38	**0.000**
Feb	May	-22.1	-28.6	-15.6	**0.000**
Feb	Jun	-15.1	-21.7	-8.56	**0.000**
Feb	Jul	4.31	-2.86	11.5	0.564
Feb	Aug	15.8	5.18	26.5	**0.000**
Mar	Apr	-4.61	-7.79	-1.43	**0.000**
Mar	May	-15.8	-19	-12.6	**0.000**
Mar	Jun	-8.84	-12.1	-5.55	**0.000**
Mar	Jul	10.6	6.27	15	**0.000**
Mar	Aug	22.2	13.1	31.2	**0.000**
Apr	May	-11.2	-13.7	-8.65	**0.000**
Apr	Jun	-4.23	-6.9	-1.56	**0.000**
Apr	Jul	15.2	11.3	19.1	**0.000**
Apr	Aug	26.8	17.9	35.6	**0.000**
May	Jun	6.94	4.28	9.6	**0.000**
May	Jul	26.4	22.5	30.3	**0.000**
May	Aug	37.9	29.1	46.7	**0.000**
Jun	Jul	19.5	15.5	23.4	**0.000**
Jun	Aug	31	22.1	39.8	**0.000**
Jul	Aug	11.5	2.24	20.8	0.005

Table S5: Results of Tukey's test of honestly significant difference of group means for an analysis of variance of mean shark depth by time of day (TOD) and lunar phase (Moon), based on pooled depth data from five individuals. Depths were adjusted for seasonal effects by subtracting a rolling monthly mean depth for each individual. Adjusted p values account for multiple pairwise comparisons, with bold values indicating significant difference in group means at the 5% level.

Group1	Group2	Group2 depth – Group1 depth (m)			Adjusted
		Estimate	UCL	LCL	p value
Day	Night	-10.800	-11.800	-9.780	**0.000**
Day:New	Day:Waxing	-1.530	-4.510	1.450	0.774
Day:New	Day:Full	-1.890	-4.960	1.170	0.568
Day:New	Day:Waning	-3.320	-6.430	-0.216	**0.026**
Night:New	Night:Waxing	3.060	0.082	6.030	**0.039**
Night:New	Night:Full	6.100	3.040	9.160	**0.000**
Night:New	Night:Waning	0.888	-2.200	3.980	0.988
Day:Waxing	Day:Full	-0.361	-3.420	2.700	1.000
Day:Waxing	Day:Waning	-1.790	-4.890	1.310	0.651
Night:Waxing	Night:Full	3.040	-0.002	6.090	0.050
Night:Waxing	Night:Waning	-2.170	-5.250	0.912	0.391
Day:Full	Day:Waning	-1.430	-4.610	1.750	0.872
Night:Full	Night:Waning	-5.210	-8.370	-2.050	**0.000**

Table S6: Comparison of candidate GLMMs to predict the median semi-diel (i.e. day/night) depth, in metres, of silvertip sharks in the Chagos Archipelago, based on data from five tags. Fixed effects tested were mixed layer depth (MLD: metres), sea surface temperature (SST: °C), lunar phase (Moon: new, waxing, full, waning), time of day (TOD: day, night) and shark total length (TL, in centimetres). The interaction between Moon and TOD was also tested to evaluate the effect of moonlight levels on shark depth. Tag ID was treated as a random factor, and a second-order autoregressive term was included in all models to account for autocorrelation within the time-series data. Models tested are presented in descending order of sample size-corrected Aikike Information Criteria (AICc), with log-likelihood and marginal/conditional R^2 (variance explained by predictors) shown for comparison of model performance. A cut off of ΔAICc < 4 was used to classify top-performing models.

Model	Fixed predictors of depth	AICc	LogLik	ΔAICc	R^2m / R^2c
13	MLD + TOD + TL	6335.2	-3159.5	0.0	0.32 / 0.32
7	MLD + TOD	6335.5	-3160.7	0.3	0.27 / 0.32
12	MLD + TOD + SST	6336.4	-3160.1	1.2	0.28 / 0.33
15	MLD + TOD*Moon + TL	6337.9	-3154.7	2.7	0.34 / 0.34
14	MLD + TOD*Moon + SST	6339.0	-3155.3	3.8	0.29 / 0.34
16	MLD + TOD*Moon + SST + TL	6339.1	-3154.3	3.8	0.34 / 0.34
11	MLD + TOD + Moon	6339.7	-3159.7	4.5	0.28 / 0.32
10	MLD + TL	6376.8	-3181.4	41.6	0.16 / 0.16
2	MLD	6377.2	-3182.6	42.0	0.1 / 0.14
9	MLD + SST	6378.4	-3182.1	43.2	0.1 / 0.15
8	MLD +Moon	6381.5	-3181.6	46.2	0.1 / 0.15
3	TOD	6413.6	-3200.8	78.4	0.13 / 0.17
6	TL	6456.8	-3222.3	121.5	0.05 / 0.05
1	Intercept only	6456.9	-3223.4	121.7	0 / 0.04
5	SST	6457.7	-3222.8	122.5	0 / 0.04
4	Moon	6459.2	-3221.5	124.0	0 / 0.04

Table S7: Correlation between characteristics of the ascent profiles for a 185 cm silvertip shark returning from mesopelagic dives below 200 m. Pearson's correlation coefficients were calculated between the depth of the breakpoint (i.e. >50% reduction) in the shark's vertical ascent rate, characteristics of the dive (dive depth and time spent below depth and temperature thresholds) and water column properties (temperature and dissolved oxygen profile).

	Breakpoint depth (m)	Max. dive depth (m)	Time below 150 m (minutes)	Time below 18°C (minutes)	18°C isotherm depth (m)	OMZ depth (m)
Maximum dive depth (m)	0.23	-				
Time below 150 m (minutes)	0.04	0.33	-			
Time below 18°C (minutes)	0.14	0.23	0.83	-		
18°C isotherm depth (m)	0.29	0.03	-0.03	-0.18	-	
OMZ depth (m)	0.35	0.09	0.08	-0.06	0.53	-
2.5 ml l^{-1} DO isopleth depth (m)	0.32	-0.04	0.03	-0.04	0.55	0.81

Supplementary figures

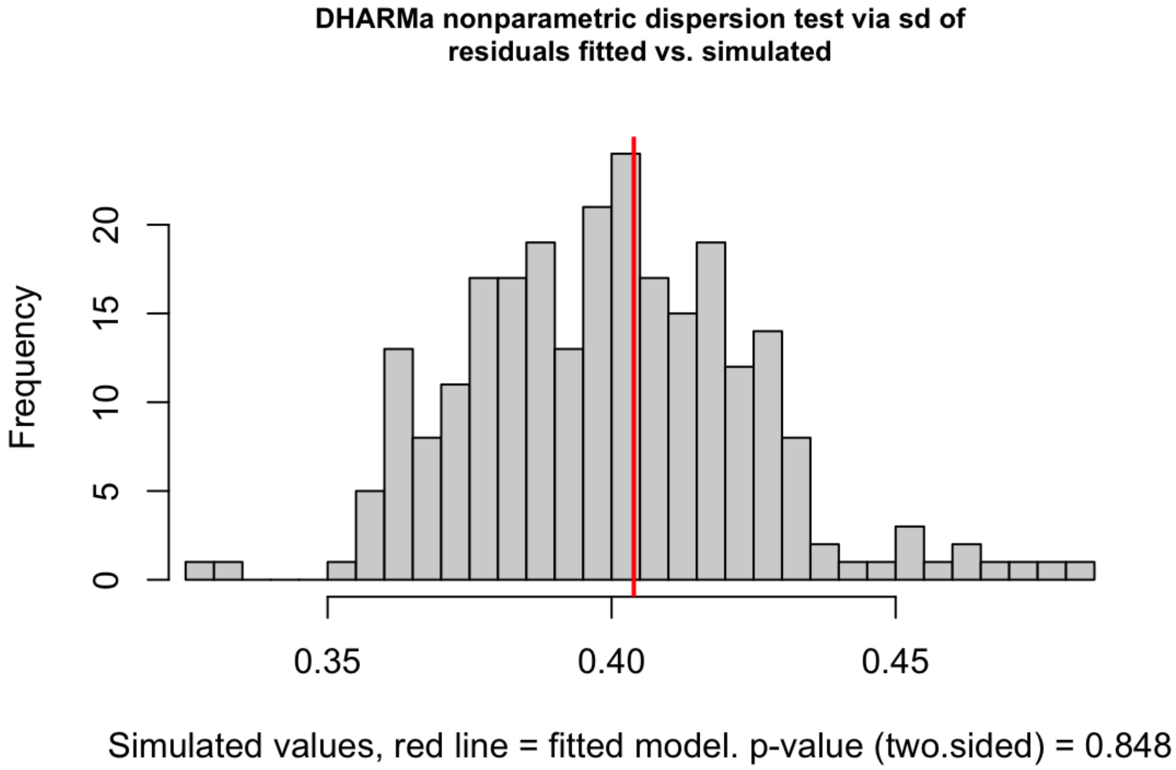

Figure S1: Plot of actual against simulated residuals using DHARMa dispersion test for the GLMM including MLD, TOD*Moon and SST as fixed effects, showing no evidence of over-dispersion at the 5% significance level.

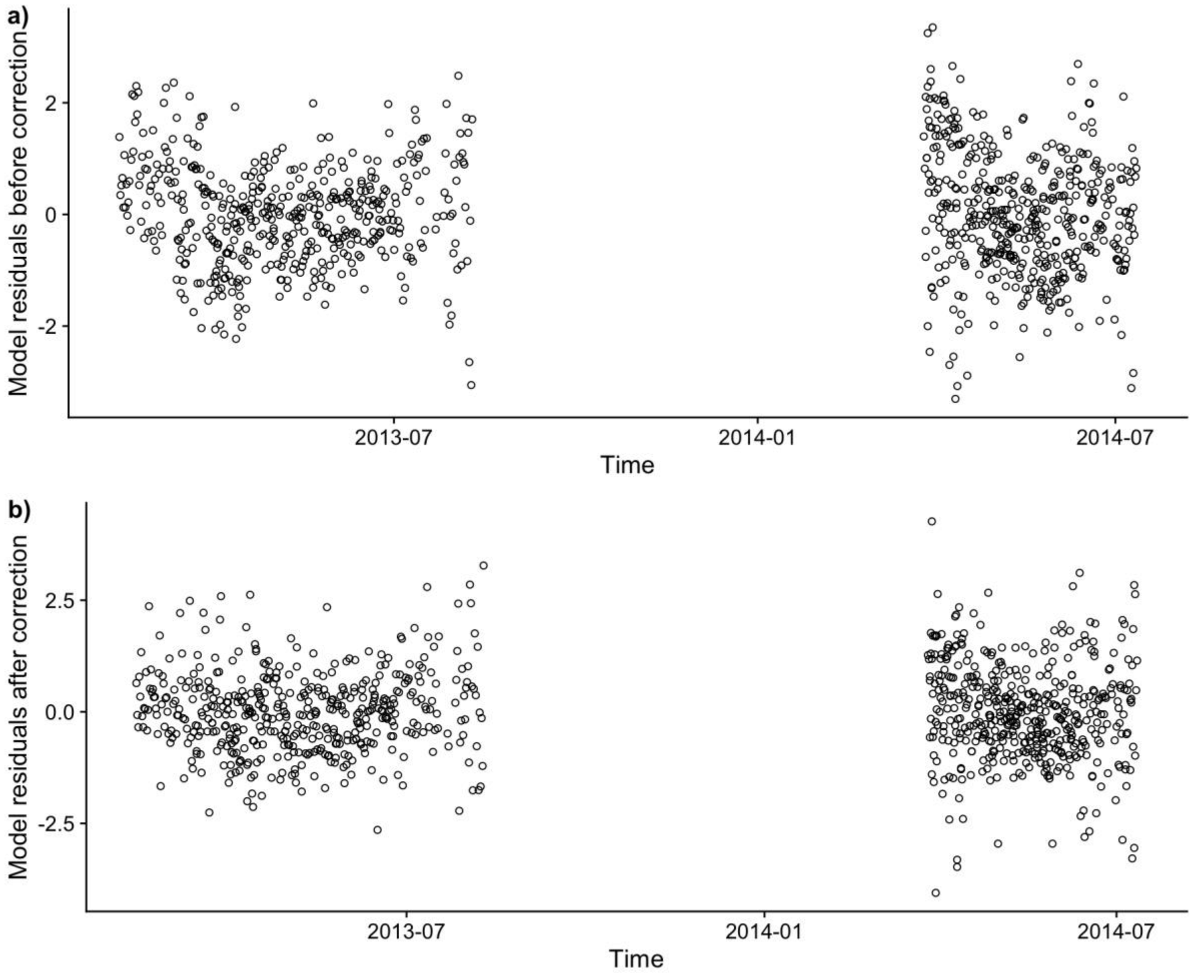

Figure S2: Plots of standardised model residuals against time a) before and b) after incorporating a second-order autoregressive term into a GLMM including MLD, TOD*Moon and SST as fixed effects.

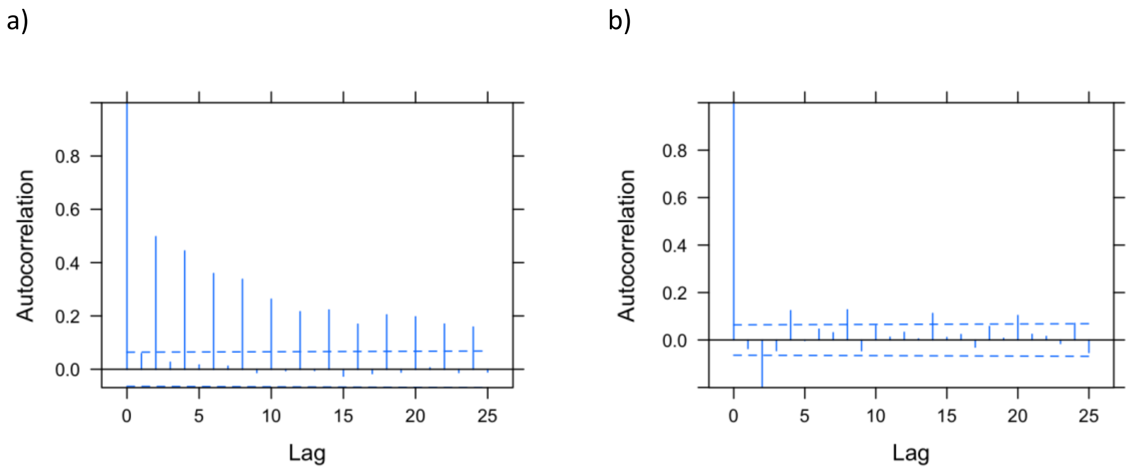

Figure S3: Autocorrelation Factor (ACF) plots of standardised model residuals a) before and b) after incorporating a second-order autoregressive term into a GLMM including MLD, TOD*Moon and SST as fixed effects. The dashed blue line indicates a significance threshold.

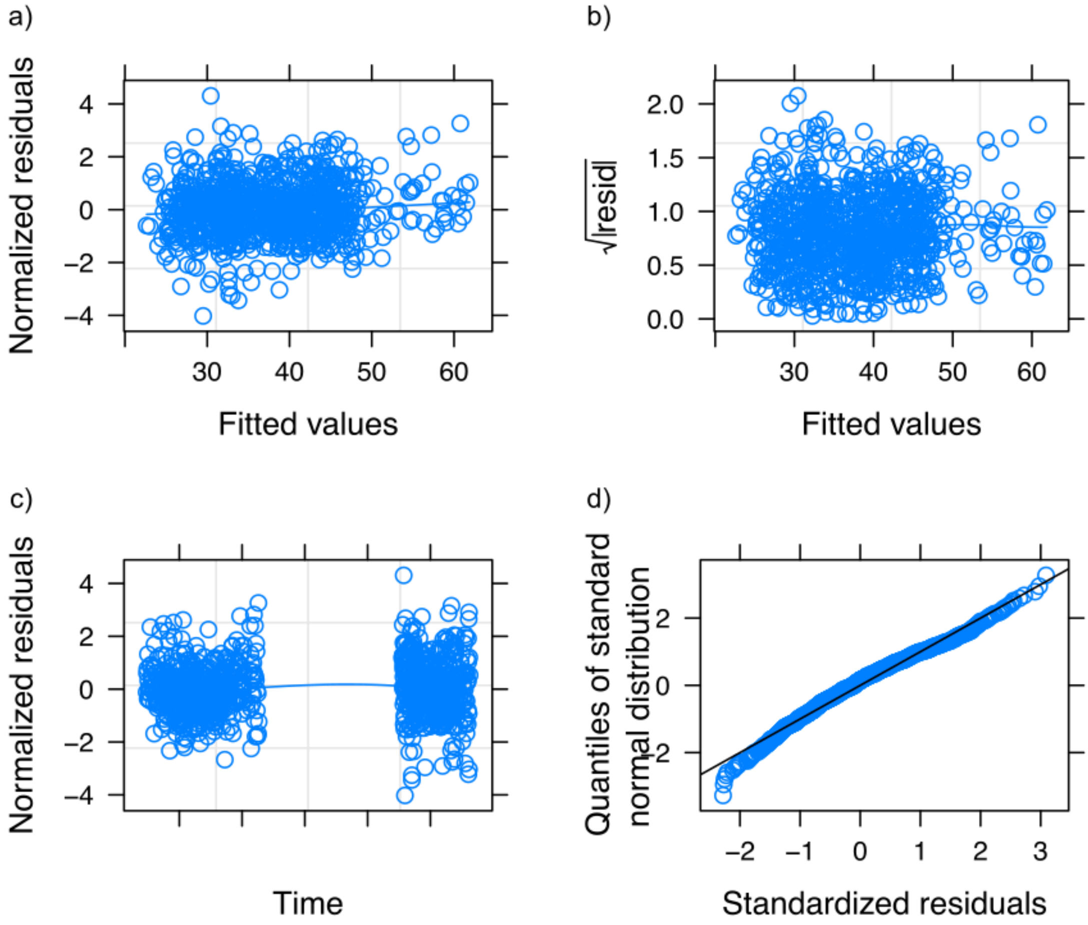

Figure S4: Diagnostic plots for the final GLMM selected to model shark depth. Fixed effect predictors were mixed layer depth (MLD: m), sea surface temperature (SST: °C), time of day (TOD: day, night), lunar phase (new, waxing, full, waning) and the interaction between time of day and lunar phase. Panels: a) Standardised residuals vs fitted values, b) Scale-location plot, c) Plot of residuals against time, and d) Q-Q plot to check normality of standardised residuals

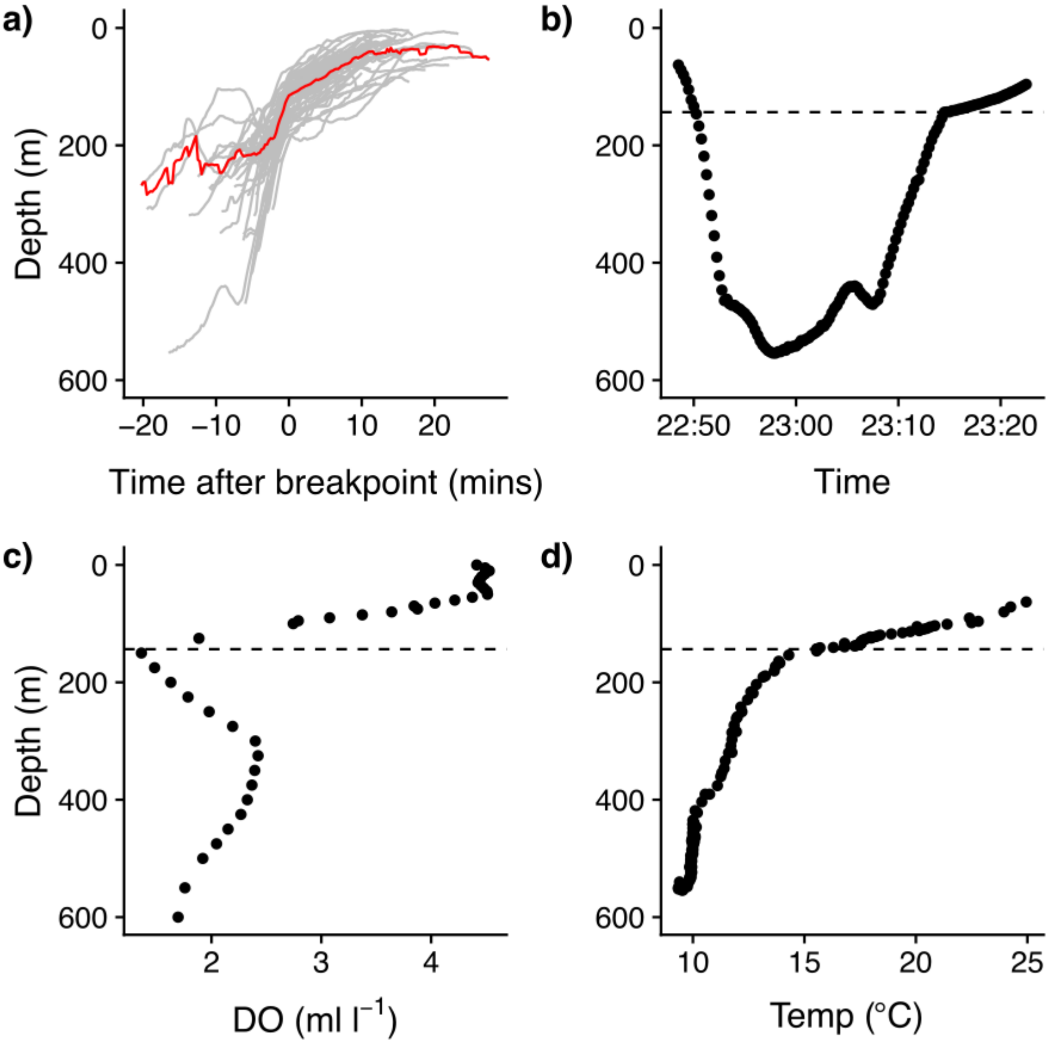

Figure S5: Exploratory plots of ascent profiles of dives by shark ID 391300800. a) Combined plots of ascent profiles of dives deeper than 200m, on a standardised time scale where t = 0 corresponds to the transition point in the shark's vertical ascent speed in each dive; the red line shows the mean depth profile of all dives; b) an example dive profile from a single dive, showing the transition point in the ascent phase, indicated with the dashed line; c) dissolved oxygen (DO) and d) temperature profiles for the same dive. Dashed lines in c) and d) indicates depth of transition point marked in panel b).

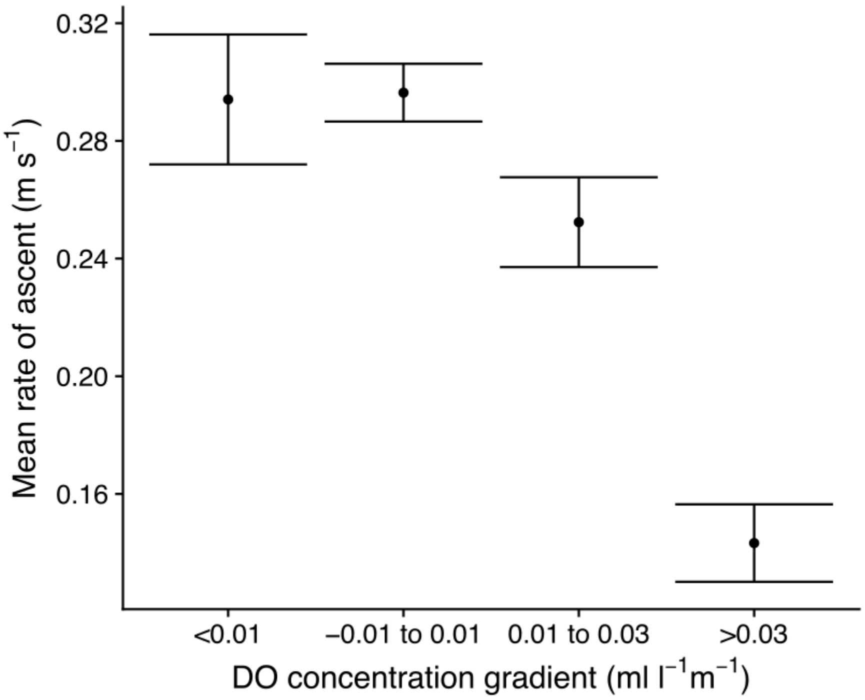

Figure S6: Relationship between the shark's mean vertical ascent rate on returning from dives, in metres per second (± CI, indicated by error bars), and the dissolved oxygen (DO) concentration gradient (increase in DO concentration in millilitres per litre per metre of vertical ascent).

S2. Supplementary methods and results

Supplementary methods

Investigation of geolocation errors

To investigate the accuracy of geolocation-based positions, we analysed data from the silvertip shark tagged with both a PAT and an acoustic tag (Tag 6, ID 391401600; Table 1) , which was detected on the passive acoustic receiver array deployed in the Chagos Archipelago at the time (Supplementary Figure S7; Tickler et al. 2019). Since the location error of acoustic detections is linked to the radius of receiver coverage, in the order of hundreds of metres (Kessel et al. 2014), position estimates derived from the acoustic tag detections were more accurate than those obtained from the light-based geolocation. For each day of the tracking period, we calculated the difference, in degrees longitude and latitude, between the daily geolocation-based position estimates from the PAT data and an average acoustic detection position, based on all receivers recording detections that day. To derive an average acoustic detection position for the shark, acoustic detections closer to local noon were given higher weight in determining the shark's daily location. The detection locations for a given day were weighted based on the absolute difference between the local time of each acoustic detection and the time of local noon, which was assumed to correspond to that day's geolocation estimate. We used the difference in latitude and longitude between each day's mean daily acoustic detection position and the corresponding geolocation estimate to calculate the difference in longitude and latitude, as well as the absolute 'error' distance in kilometres. Great circle distance was calculated using the function distGeo() in the R package *geosphere* (Hijmans 2017). We compared the distance between acoustic and geolocation positions against the difference between the mean time of the daily acoustic detections and that of the geolocation estimates (local noon) to determine whether the shark could have reasonably travelled between the two locations in the time available, based on an average swimming speed of 0.7 ms^{-1} (Ryan et al. 2015).

Description of custom window function used to analyse dive ascent profiles

At each time step in the depth-time series, the function evaluated the average rate of change of depth with time within a defined window either side of the point being evaluated. The window width was initialised at two minutes (i.e. eight 15 s time steps) either side of the time step being evaluated, and the average ascent rate in the sections before and after was calculated. The minimum reduction in ascent rate required to qualify as a breakpoint was initialised to 80%, and reduced in 10% increments to a minimum of 50% if a qualifying point in the ascent trajectory could not be found. If no qualifying point was found, the window width either side of the test point was reduced from two minutes to one minute in steps of 15 s, and the process was repeated for each change in window width. If no qualifying point was found the algorithm moved to the next dive in the timeseries. When a breakpoint was found in a dive, the time, depth, temperature and instantaneous ascent rate change at this point were passed as the function's result.

Supplementary results

Estimation of geolocation error over time

To better understand the potential geolocation error associated with the PAT data, geolocation estimates for one shark (Tag 6, ID 391401600) were compared with more precise location estimates based on detections by fixed acoustic receivers of an acoustic tag deployed on the same animal (Supplementary Figure S7). The maximum difference between the daily geolocation-based position estimates and the true daily positions derived from acoustic telemetry was 0.2 degrees longitude and 0.25 degrees latitude, or ~20 km and ~25 km, respectively (Supplementary Figure S8). Geolocation-based longitude estimates oscillated east and west around the shark's actual position (Supplementary Figure S8a), whereas geolocation-based latitude estimates showed a consistent northerly drift, with the margin of error increasing over time (Supplementary Figure S8b). Daily geolocation-based position estimates were up to 35 km from the corresponding acoustic telemetry-derived locations, in most cases well beyond the shark's likely range of movement in the available time, meaning that the shark could not have been both detected by the acoustic receivers and present at the estimated geolocation position on the same day (Supplementary Figure S9).

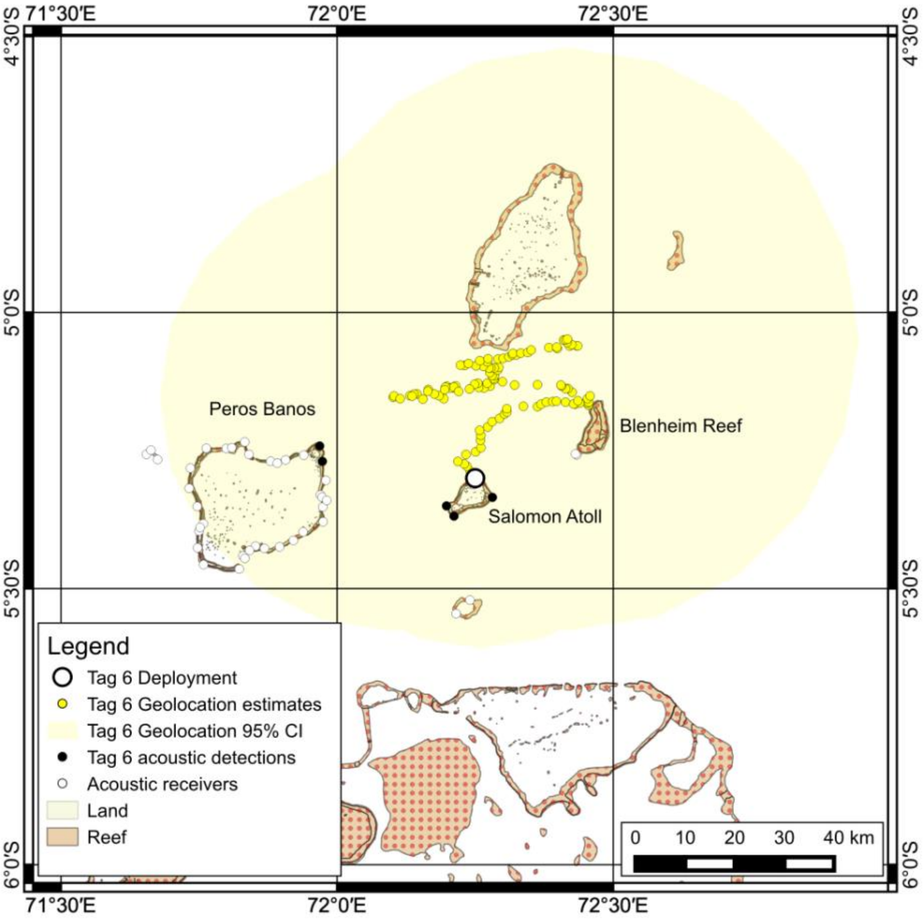

Figure S7: Map of the northern Chagos Archipelago, showing overview of telemetry data received from a double-tagged silvertip shark (Tag 6, ID 391401600), tagged with both a PAT and an acoustic tag in March 2014. The PAT-derived daily geolocation estimates and associated 95% confidence interval are shown with yellow circles and the yellow shaded area, respectively. Small black and white circles indicate locations of acoustic receivers deployed in 2014, both with and without recorded detections of the shark. Daily 'fixes' of the shark using the acoustic receiver network were used to evaluate the (in)accuracy of the PAT geolocation estimates.

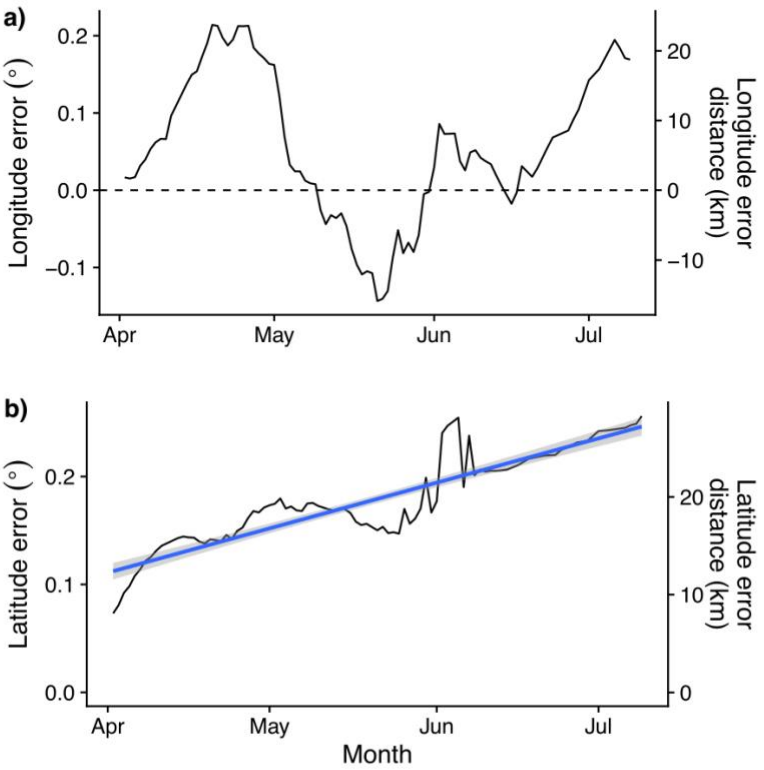

Figure S8: Difference between PAT-derived geolocation estimates and acoustic tag detection locations for a silvertip shark (Tag 6, ID 391401600) tagged with both tags in March 2014. Y-axes show difference (i.e. error), in degrees of a) longitude and b) latitude, between each day's geolocation-based position estimate and the average of the same day's acoustic detection locations, assuming that the acoustic tag-derived positions are the true position of the shark. Secondary y-axes show the position error in kilometres at the BIOT's latitude. Blue trend line and grey ribbon in (b) indicate the slope (± 95% CI) of the relationship between latitude error and time (intercept = 0.11 ± 0.004 degrees/12.1 ± 0.4 km, slope = 0.04 ± 0.002 degrees/4.9 ± 0.3 km per month, model $R^2 = 0.80$, $p < 0.001$)

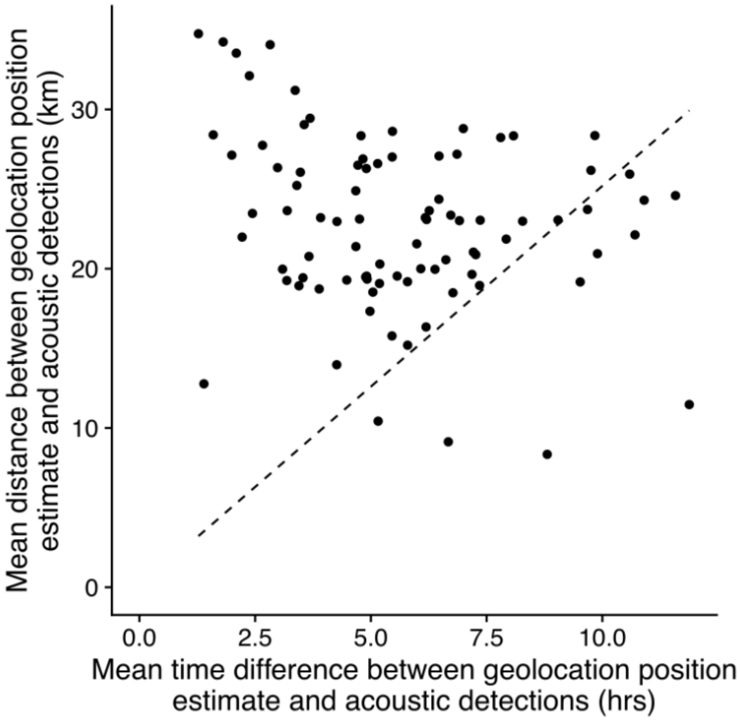

Figure S9: Distance between the daily geolocation position estimate and the mean daily acoustic telemetry derived position, in kilometres, compared with the mean time difference, in hours, between the two position estimates. The dashed diagonal line indicates the distance that could have been covered in a given time by a shark swimming at 0.7 ms^{-1}, the mean swim speed for silvertip sharks reported by Ryan et al (2015). Points above the dashed line are instances when the differences between geolocation position and acoustic tag position cannot be accounted for by shark movement, indicating geolocation error.

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S3. R code

Custom R functions

R code to identify dives in archival tag data

```
################################################################################
#########################

# Identifies all dives below 150m. Dive starts and ends when shark crossed 100m isobath.
# Takes a dataframe of archival tag data (Time, Depth, Temp) as its input

find_dives = function(tag.data) {

 # Initialise an empty list to store data for individual dives

 dives = list()

 # Initialise variables for algorithm and parameters to define dives

 start = 1; end = 1 # Initial indices of dive start and end
 dmax.index = 1 # Initial index of first maximum
 i = 1 # Index of dives
 d.thresh = 150 # Minimum max dive depth to qualify as a dive
 d.thresh.upper = 100 # Depth at which a dive is deemed to start

 # Find local maximum and minimum depth points

 # Define deep maxima as change of direction (down to up) below 150m.

 # introduce small depth correction (1 cm) to consecutive identical depth measurements to
elimimate flat spots in depth trend for ease of finding maxima/minima

 series$Depth2 = c(series$Depth[1], sapply(2:length(series$Depth), function(i)
ifelse(series$Depth[i] == series$Depth[i-1], series$Depth[i] + 0.01, series$Depth[i])))

 maxima = intersect(which(diff(sign(diff(series$Depth2)))==-2)+1, which(series$Depth >
d.thresh))

 # Define shallow minima as change of direction (up to down) above 100m.

 minima = intersect(which(diff(sign(diff(series$Depth2)))==2)+1, which(series$Depth <
d.thresh.upper))

 while(dmax.index <= max(maxima)) { # Look at all maxima below dive threshold (150m)
```

```
  dmax.index = min(intersect(maxima, end:nrow(series))) # find next maxima not already
evaluated

  # define a window around each depth maxima defining the point when the shark left and
returned to the 0-100 m layer

  start = max(intersect(minima, 1:dmax.index)) # find previous minima

  end = min(intersect(minima, dmax.index:nrow(series))) # find subsequent minima

  dives[[i]] = series[start:end, c("POSIXct.time.LCL", "Depth", "Temp")]

  i = i+1
 }

}
```

Custom function to identify breakpoints in dives

```
#####################################################################

# Function to identify local discontinuities in ascent rate (breakpoints) in the ascent portion of dives.
# Takes a list of dive profiles from archival tag data: Required fields are Time (POSIXct.time), Depth (numeric) and Temp (numeric).

find_breakpoints = function(dives){

 # Initialise packages and variables

 require(ecp)

 thresh.start = 0.2 # start looking for breakpoints where ascent rate after breakpoint is <=20% ascent rate before breakpoint
 thresh.max = 0.5 # ascent rate after breakpoint can be no more than half ascent rate before breakpoint
 window.start = 8 # Initialise width of window (number of time steps) in which I look for a rate change to 2 mins or 8 time steps
 window.min = 4 # Stop looking when window width is reduced to 1 min or 4 time steps

 # Dataframe to store results

 results = data.frame(dive = 1:length(dives), # index of dive in the list of dives
           breakpoint.index = NA, # rownumber of breakpoint in the dive data
           breakpoint.time = NA, # rownumber of breakpoint in the dive data
           breakpoint.depth = NA, # rownumber of breakpoint in the dive data
           breakpoint.temp = NA, # rownumber of breakpoint in the dive data
           rate.delta = NA, # rate of ascent change at breakpoint
           win.val = NA, # window width used
           thresh.val = NA # threshold rate change used
 )

 min.gap = 5 # breakpoint must be this many metres shallower than max depth
 min.asc.rate = 5 # metres ascent per time step (15s) to qualify as ascending = 0.3m/s

 # Examine each dive the in the list

 for (i in dives){

  temp = dives[[i]]

  if(max(temp$Depth)<200) next # Only consider dives 200m or deeper

  # Initialise vectors to store exploratory results
```

```
  breakpoints = numeric() # stores a vector of candidate breakpoints
  rate.delta = numeric() # local change in ascent rate at breakpoint
  thresh.val = numeric() # threshold value for ascent rate change used
  win.val = numeric() # window width used

  thresh = thresh.start # initialise threshold to lowest value

  # search for breakpoint within rate change and window constraints until a breakpoint is
found or the search constraints are exceeded

  while(length(rate.chg) == 0 & thresh <= thresh.max) {

   window = window.start # initialise window to maximum value

   while(length(rate.chg) == 0 & window >= window.min){

    # I track the index of the time step for the dive (k)
    # Only look for inflections after the deepest point of the dive
    for (k in max(which(temp$Depth == max(temp$Depth))):length(temp$Depth)-window){
# set search range between last time at max depth and the end of the dive time series

     # Check that the breakpoint is happening during an ascent phase and is above 200m (i.e.
not oscillations at depth) and below the thermocline (Temp <22 deg C)
     if(mean(diff(temp$Depth[(k-window):k]))<0 & mean(diff(temp$Depth[k:(k+window)]))<0
& temp$Depth[k]<200 & temp$Temp[k] < 22) {

      # Check that the ascent rate difference before and after the breakpoint is less than the
threshold criteria (range 20% to 50% of pre-breakpoint rate)
      if(mean(diff(temp$Depth[k:(k+window)]))/mean(diff(temp$Depth[(k-
window):k]))<=thresh & abs(mean(diff(temp$Depth[(k-window):k]))) > min.asc.rate) {

       # add constraint that all time steps must have same sign (i.e. are part of a continuous
ascent not an ascend/descend sequence)

       # check that the shark does not dive again

       if((temp$Depth[k]+min.gap) > max(temp$Depth[(k+1):length(temp$Depth)])) {

        # add the time step to the vector of inflection points
        breakpoint.index = c(breakpoint.index, k)

        # store the parameters of the breakpoint
        rate.delta = c(rate.delta,
mean(diff(temp$Depth[k:(k+window)]))/mean(diff(temp$Depth[(k-window):k])))
        thresh.val = c(thresh.val, thresh)
        win.val = c(win.val, window)
```

```
       }
      }
     }
    }
    # If no qualifying breakpoint found, make the window shorter and try again
    window = window - 1
   }

   # If no breakpoint found with the initial rate threshold increase the rate change threshold and try again
   thresh = thresh + 0.05
  }

  if(length(rate.chg) == 0) next # skip to next dive if no breakpoint was found

  # In multiple candidate breakpoints are identifies, use the breakpoint with the greatest ascent rate reduction

  j = breakpoints[rate.delta == min(rate.delta)][1]

  results[i, ]$breakpoint.index = j
  results[i, ]$breakpoint.time = temp[j,]$Time
  results[i, ]$breakpoint.depth = temp[j,]$Depth
  results[i, ]$breakpoint.temp = temp[j,]$Temp
  results[i, ]$rate.delta = rate.delta[rate.delta == min(rate.delta)][1]
  results[i, ]$thresh.val = thresh.val[rate.delta == min(rate.delta)][1]
  results[i, ]$win.val = win.val[rate.delta == min(rate.delta)][1]

 }

 return(results)

}
```