

Contrasting movement strategies among juvenile albatrosses and petrels

Sophie de Grissac* ^{a,b}, Luca Börger ^c, Audrey Guitteaud ^a and Henri Weimerskirch ^{a,b}

Supplementary Information

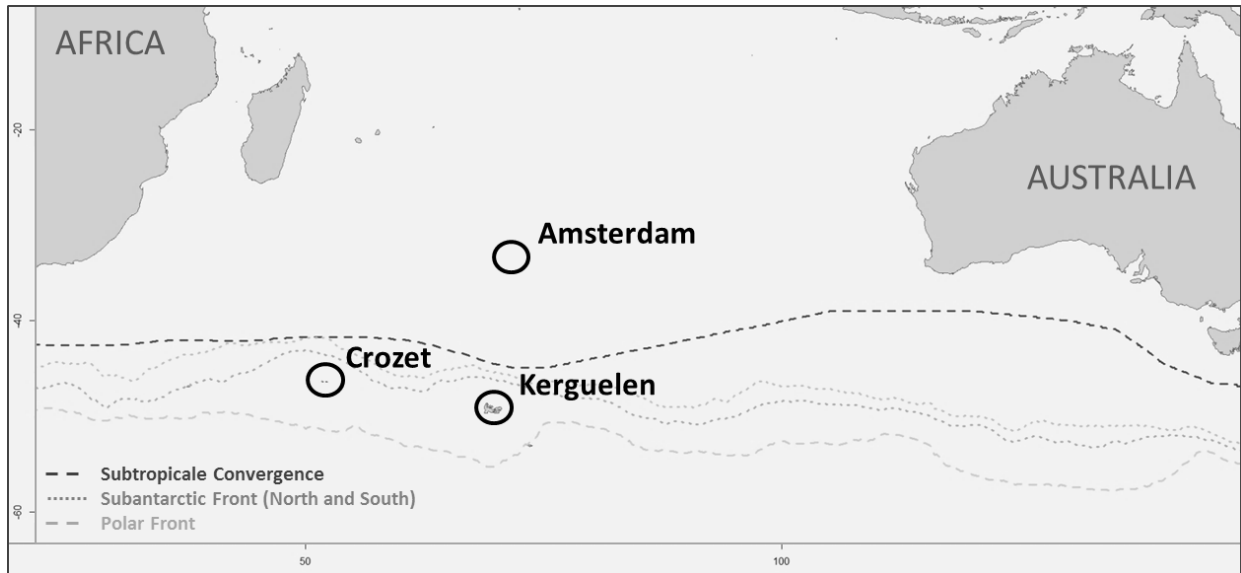
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Supplementary Fig.1. Map of study colonies in the Indian Ocean



The map has been generated with R v3.2.3 (R Core Team, 2014) and the ‘ggplot2’ (Wickam, 2009) library and free-access coastline data (from naturalearthdata.com). Polar and sub Antarctic Front have been calculated from Aviso products (Altimetric Sea Level Anomaly of Sallee *et al.*, 2008) available online at <http://ctoh.legos.obs-mip.fr/applications/mesoscale/southern-ocean-fronts>. Subtropical Convergence data come from Belkin & Gordon (1996).

References

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Supplementary Methods 1. Telemetry data preparation and tracking

duration

Telemetry data preparation

For juveniles, all Argos locations (classes A, B, 0, 1 to 3) were used. Unrealistic positions were filtered out by removing those with an estimated speed above 90km/h (McConnell *et al.* 1992). Because of the use of duty cycled transmitters with varying duty-cycles, significant disparities in location frequency occurred between individuals. In order to make comparisons between individuals with similar location frequencies, we resampled the time series to obtain a maximum of one location every 10h, removing intermediate locations when necessary. This resulted in tracks with a mean of 0.65 ± 0.12 locations per day with time between locations varying from 10 to 72h. Some trajectories were discarded because the tracking time was too short or locations were too infrequent because of tag malfunction, giving a total of 83 tracks including 53 tracks lasting at least 3 months used for the analyses.

Tracking duration

We chose to analyse only the 3 first months of juvenile's trajectories because more than 50% of juvenile's tags stopped before 100 days. Tags were very similar for most species, and there was no reason for them to differ in duration of transmission or likelihood of failure. Yet when looking closely at the duration of transmission of tags, it was obvious it differed between species, and that the smaller the species, the shorter the transmission. This may be either because the mortality of smaller species is higher, or because the attachment of tags on smaller species is less efficient since the tags used are basically of the same size. Since back

65 feathers on smaller species are smaller and more likely to be detached after a certain time,
66 this latter hypothesis is the most likely.

67

68 **References**

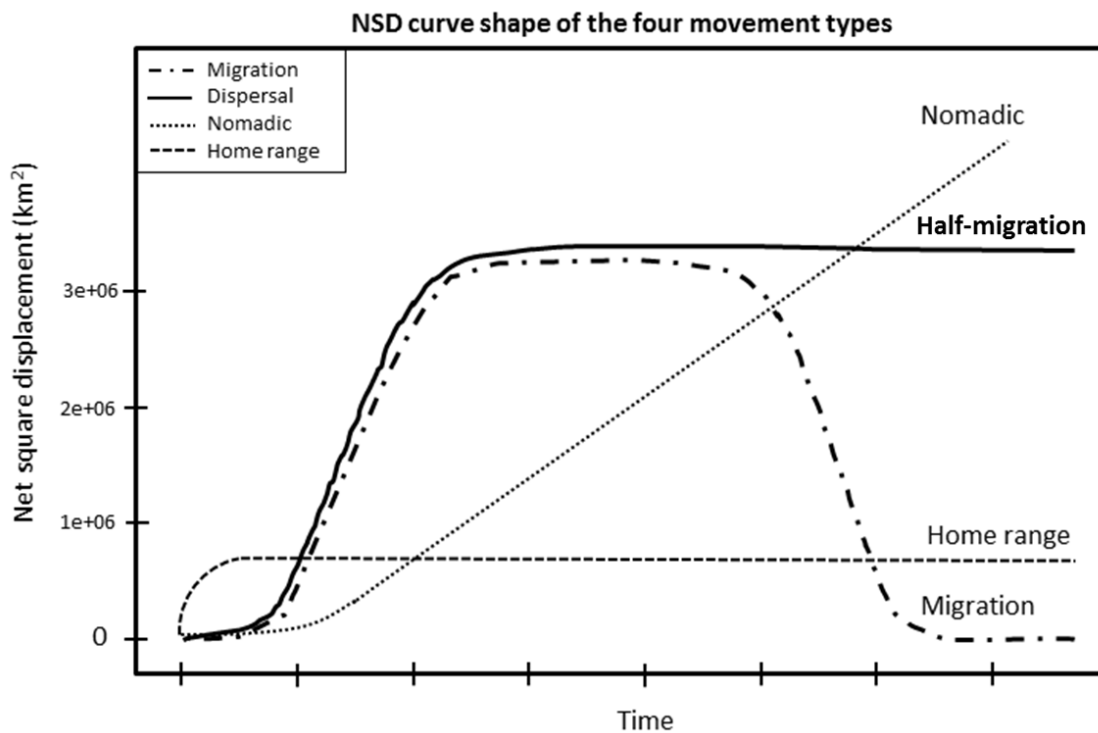
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Supplementary Methods 2. Complement to methods: net squared displacement analyses

Methods 2. Fig.1. Typical NSD (Net Square Displacement from departure colony) over time curve shapes of the four movements types, adapted from (Bunnefeld *et al.* 2011).



The model we termed here “half-migration” corresponds to the “Half-migration” model of Bunnefeld *et al.* (2011) and Börger & Fryxell (2012). We renamed it for consistency with juvenile and adult strategies and because juveniles will eventually return to their natal grounds completing, with time, a “true migratory” trip.

Methods 2 - Equation 1. Equations of the four NSD models (Borger & Fryxell 2012). t is the time since start. D and b are the diffusion constant and exponent. $Asym$ is the asymptote at the settlement (km^2) and quantifies the movement distance. θ is a parameter for the inflexion point, in units of time since start (t), and thus models the timing of the transience phase. ϕ is a scale parameter on the time axis governing the shape of the curve.

$NSD^2 = D \times t^b$	Home-range
$NSD^2 = Asym \times (1 - e^{-at})$	<u>Nomadism</u>
$NSD^2 = \frac{Asym}{1 + \exp\left(\frac{\theta - t}{\phi}\right)}$	Half-migration
$NSD^2 = \frac{Asym}{1 + \exp\left(\frac{\theta_a - t}{\phi_a}\right)} + \frac{-Asym}{1 + \exp\left(\frac{\theta_b - t}{\phi_b}\right)}$	Migration

Methods 2.1. NSD calculation for circumpolar trajectories.

For species making multiple circumpolar trips by flying continuously in the same direction (Figure 2.a left), the NSD values increase until they reach the longitude opposite to their departure colony (colony longitude $- 180^\circ$) then they decrease until they reach the departure longitude. To avoid this artefact in distance calculations, we modified the calculation of the NSD in order to keep the continuously increasing flight distance characteristic of the trajectory. Specifically, the NSD was calculated as if the birds kept flying away from their departure point; see Fig.2.a, right panel, in the main text. For comparison, Fig 2.b, left panel, main text, shows a trajectory typical of the half-migration type model.

Methods 2.2. Identification of the large-scale looping type movement.

We identified a movement mode not originally considered in the (Borger & Fryxell 2012) approach, termed large-scale looping movement. It is characterized by individuals remaining in the Indian Ocean for all three months after leaving the natal colony, but with large and frequent foraging loops within the Indian Ocean, reaching up to >1000km distance from the natal colony, then coming back again close to the departure area (e.g. Fig. 2c).

Methods 2.3. Movement scale and habitat preference of adults.

In order to characterize the large scale strategy of adults we used the asymptote distance from colony (i.e. migration distance) given by the migratory NSD model fitted to each trajectory as an estimation of the inter-breeding movement scale. The residuals of the model (variation of the NSD around the asymptote) give an estimation of displacement and wintering area scales. We determined the bathymetric characteristics of the wintering areas (neritic/oceanic) by looking broadly at the trajectories but GLS data do not permit to calculate precise bathymetric characteristics of the zones foraged.

References

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Supplementary Methods 3. Complement to methods: trajectory parameters analyses

Orientation

Absolute flight directions were estimated as the loxodromic (or rhumb) flight bearings in relation to the geographic North. We first calculated heading at departure, arbitrarily chosen as the mean of the absolute directions taken during the first ten days since departure. Then we calculated the bearing of the positions at two and three months, i.e. the loxodromic direction of the position on the first day of each month from the colony location. For circumpolar trajectories, we corrected for the artefact of direction reversal once the longitude opposite to the departure point is crossed (i.e. $> 180^\circ$) by setting the bearings as “bearing – π ”.

Sinuosity

The large scale sinuosity of the trajectories was calculated over 15 day time windows as follows: $S = 1 - D_a/D_b$, with D_a the beeline distance between $loc(t_1)$ and $loc(t_n)$ and D_b the real distance travelled between $loc(t_1)$ (day 1 of the time window) and $loc(t_{15})$ (day 15 of the time window).

Daily distance travelled

At this scale, the DDT (distance travelled per 24 hours) we calculated integrates flight speed, time-spent on water and small scale sinuosity. Distance to colony: We calculated the loxodromic distance to the natal colony from each location of the trajectory (range) and computed the mean and the standard deviation for 3 time periods for each individual (1, 2 and

149 3 months after departure). The standard deviation gives an indication of the space-scale
150 dispersion of locations. An individual with a low range standard deviation tends to stay in a
151 small area around the mean range value whereas a bird with a high range standard deviation
152 tends to forage in a large area around the mean range value or tends to keep going away from
153 the starting point.

154 **Mean latitude**

155 We tested for differences in mean latitude of the trajectory of juveniles and adults using the
156 Wilcoxon test. As there were no significant differences within species between birds from
157 different colonies (Wilcoxon test: $P > 0.1$), for adults and juveniles, we did not separate
158 individuals by colony of origin.

159 **Note about test significance and sample size**

160 With only one juvenile yellow-nosed albatross tracked more than three months, tests for this
161 species cannot be reliable and in those cases, prior assumptions to modelling were often not
162 respected. The same is true for southern giant petrels after 1.5 month (only two individuals
163 left), Light-mantled sooty albatrosses after 2 month and white-chinned petrels for the last
164 period (after 2.5 month).

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Supplementary Table 1. Goodness of fit values of NSD models fitted on individual 3 months trajectories.

Goodness of fit values are calculated for the 4 NSD model types applied to each juvenile. The null model (NSD² = constant) is used as a reference. Models for which the parameter outputs (asymptote timing and distance) are out of the data range are pointed out by an asterisk. The best model is the one with the highest GOF value and consistent parameter outputs. The asymptote distance returned by the best model is given in km along with the distance from colony at the end of the 3 months corresponding to a dispersion distance category (see Methods).

Northern giant petrel (NOGP)

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
87436	0.000	0.551	0.992	0.923	0.725*	Half-migration	Kerguelen	14948	14305	large
87470	0.000	0.571*	0.961	0.970	0.610*	Nomad	Crozet	-	20555	large
87471	0.000	0.555	0.995	0.908	0.733*	Half-migration	Crozet	16845	15841	large
87476	0.000	0.613*	0.959*	0.954	0.429*	Nomad	Crozet	-	17146	large
87478	0.000	0.644*	0.986*	0.983	0.526*	Nomad	Kerguelen	-	15895	large
87480	0.000	0.560*	0.896*	0.916	0.589*	Nomad	Kerguelen	-	20365	large

Southern giant Petrel (SOGP)

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
87466	0.000	0.219*	0.988*	0.990	0.106*	Nomad	Crozet	-	25411	Large
87474	0.000	0.297*	0.987*	0.994	0.066*	Nomad	Crozet	-	22251	large

176

177 **Yellow-nosed albatross (YNAL)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
103667	0.000	0.886	0.939	0.773	0.927*	Half-migration	Amsterdam	4393	4869	Medium
79356	0.000	0.831	0.991	0.738	0.837*	Half-migration	Amsterdam	3436	3486	medium

178

179 **Black-browed albatross (BBAL)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
103665	0.000	0.751	0.970	0.850	0.855*	Half-migration	Kerguelen	4530	4555	medium
103666	0.000	0.971*	0.976*	0.980	0.690*	Nomad	Kerguelen	-	9170	large
132031	0.000	0.562	0.975	0.780	0.715*	Half-migration	Kerguelen	5120	5144	medium
132032	0.000	0.793	0.987	0.886	0.874*	Half-migration	Kerguelen	5674	5836	medium
132034	0.000	0.706	0.990	0.846	0.830*	Half-migration	Kerguelen	5470	5428	medium
132038	0.000	0.811	0.988	0.779	0.679*	Half-migration	Kerguelen	5717	5713	medium
132039	0.000	0.917	0.983	0.903	0.782*	Half-migration	Kerguelen	5386	5456	medium

180

181 **White-chinned petrel (WCPE)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
67413	0.000	0.852*	0.963	0.885	0.403*	Half-migration	Crozet	4611	4806	medium
87481	0.000	0.880*	0.904	0.885	0.713*	Half-migration	Kerguelen	4638	3902	medium
87482	0.000	0.951*	0.960	0.950	0.741*	Half-migration	Kerguelen	4154	3951	medium
87485	0.000	0.924*	0.953	0.933	0.764*	Half-migration	Kerguelen	3811	3650	medium

182

183 **Light-mantled albatross (LMSA)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
87459	0.000	0.6761*	0.809	0.669	0.87	Migratory	Crozet	1786	1550	Small
87460	0.000	0.064	0.109	0.0068*	0.886	Migratory	Crozet	1658	1632	Small
87487	0.000	0.100	0.14	0.0085*	0.913*	Half-migration	Kerguelen	2594	3253	Medium
87489	0.000	0.086	0.201	0.003*	0.862*	Half-migration	Kerguelen	2636	1225	small

184

185 **Sooty albatross (SOAL)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
34137	0.000	0.149	0.110	0.094	0.127*	Home-range	Amsterdam	1123	1356	small
34145	0.000	0.024	0.022	-0.006	0.123*	Home-range	Amsterdam	1270	1369	small
66209	0.000	0.130	0.094	0.233	-0.076*	Nomad	Crozet	-	2183	small
67410	0.000	0.381	0.406	0.523	0.493*	Nomad	Crozet	-	1908	small
67411	0.000	0.086	0.019	-0.169	0.299*	Home-range	Crozet	1664	878	small
87465	0.000	0.262	0.253	0.349	0.353*	Nomad	Crozet	-	2853	small
93725	0.000	0.191	0.114	0.033	0.189*	Home-range	Amsterdam	1552	1237	small

186

187 **Amsterdam albatross (AMAL)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
112947	0.000	0.236*	0.515	0.241	0.354*	Half-migration	Amsterdam	1840	2158	Small
112948	0.000	0.236*	0.779	0.502	0.637*	Half-migration	Amsterdam	3114	447	Small
112950	0.000	0.281*	0.752*	0.719	0.735*	Nomad	Amsterdam	3579	2825	Medium
40660	0.000	0.297*	0.971*	0.590	0.480*	Nomad	Amsterdam	3935	3141	Medium
53936	0.000	0.435*	0.703	0.710	0.686*	Half-migration	Amsterdam	2841	2656	Small
53937	0.000	0.170*	0.963	0.887	0.938*	Half-migration	Amsterdam	4300	4292	Medium
53938	0.000	0.163*	0.973*	0.965	0.967*	Nomad	Amsterdam	5221	5278	medium

188

189 **Wandering albatross (WAAL)**

Trip ID	Null	Home-Range	Half-migration	Nomad	Migratory	Best model	Colony	Asymptote distance	Range at 3 months	Dispersion scale
11817	0.442	0	0.316	0.453	0.456*	Nomad	Crozet	-	2231	small
1391	0.836	0	0.799	0.949	0.783*	Nomad	Crozet	-	4905	large
25751	0.280	0	0.154	0.320	0.167*	Nomad	Crozet	-	584	small
38557	0.630	0	0.913	0.590	0.706*	Half-migration	Crozet	5993	5693	large
38558	0.794	0	0.924	0.825	0.885*	Half-migration	Crozet	5970	6278	large
38559	0.088	0	0.373	0.153	0.071*	Half-migration	Crozet	1466	748	small
78345	0.240	0	0.527	0.184	0.479*	Half-migration	Kerguelen	3957	2052	medium
78346	0.906	0	0.993	0.903	0.979*	Half-migration	Kerguelen	5961	6105	large
78348	0.919	0	0.991	0.908	0.990*	Half-migration	Kerguelen	6497	6719	large

78349	0.584	0	0.712	0.549	0.674*	Half-migration	Kerguelen	3925	3797	medium
78350	0.726	0	0.899	0.686	0.882*	Half-migration	Kerguelen	4772	3871	medium
78351	0.906	0	0.977	0.944	0.951*	Half-migration	Kerguelen	6633	6846	large
78352	0.319*	0	0.964*	0.959*	0.241*	No fit	Kerguelen	-	5974	large
8959_01	0.309	0	0.283	0.324	0.293*	Nomad	Crozet	-	1436	small
8959_02	0.782*	0	0.974	0.982	0.719*	Nomad	Crozet	-	6956	large
8960_01	0.619	0	0.913	0.896	0.532*	Half-migration	Crozet	2148	2667	medium
8960_02	0.915	0	0.976	0.940	0.953*	Half-migration	Crozet	6847	6977	large
9059	0.510	0	0.855	0.761	0.443*	Half-migration	Crozet	1912	2530	medium

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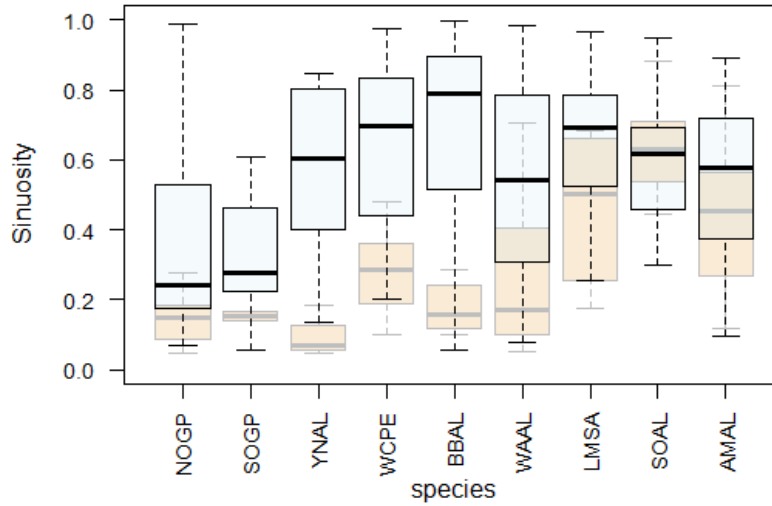
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Supplementary Results 1. Sinuosity: comparison between species



Boxplots of the sinuosity by species, during the first 15 days (cream & grey boxes) and averaged over the rest of the trajectories (15 days to 3rd month, blue & black boxes). Horizontal bars are the median, box limits are upper and lower quartiles, whiskers represent dispersion.

Linear mixed model results:

Model: Sinuosity ~ species + random = ~1 | individual

SPECIES	Value	Std.Error	DF	t-value	p-value
(Intercept: NOGP)	0.326	0.039	287	8.293	0
SOGP	-0.027	0.071	73	-0.387	0.6996
YNAL	0.121	0.087	73	1.391	0.1685
WCPE	0.235	0.060	73	3.886	0.0002
BBAL	0.257	0.055	73	4.719	0
WAAL	0.150	0.050	73	3.020	0.0035
LMSA	0.279	0.069	73	4.040	0.0001
SOAL	0.272	0.055	73	4.971	0
AMAL	0.201	0.056	73	3.619	0.0005

Notes: Treatment contrasts were used, hence the parameter estimate for the Intercept corresponds to the first species, here NOGP, ('reference value'), whilst all other values are the estimated differences compared to the first ('reference') species.

Post-hoc Tukey test p-values:

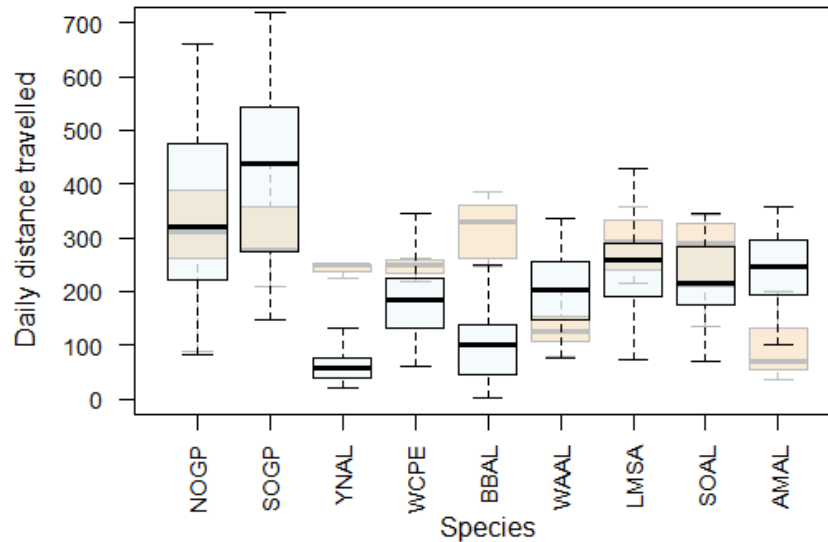
SPECIES	NOGP	SOGP	YNAL	WCPE	BBAL	WAAL	LMSA	SOAL	AMAL
NOGP									
SOGP	1								
YNAL	0.8951	0.835							
WCPE	<0.01	0.0122	0.9378						
BBAL	<0.01	<0.01	0.8075	1					
WAAL	0.0599	0.1455	1	0.8187	0.3701				
LMSA	<0.01	<0.01	0.7701	0.9996	1	0.5171			
SOAL	<0.01	<0.01	0.7046	0.9994	1	0.2083	1		
AMAL	<0.01	0.0306	0.9909	0.9998	0.9826	0.9795	0.9689	0.9305	

P < 0.05 are highlighted in dark cream, 0.05 < P < 0.1 are highlighted in light cream color. Note that the YNAL sample is too small to give relevant results.

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Supplementary Results 2. Daily distance travelled: comparison between species



Boxplots of the daily distance travelled by species, during the first 15 days (cream & grey boxes) and averaged over the rest of the trajectories (15 days to 3rd month, blue & black boxes). Horizontal bars are the median, box limits are upper and lower quartiles, whiskers represent dispersion.

Linear mixed model results with the first species as intercept:

Model: DDT ~ species + random = ~1 | individual

SPECIES	Value	Std.Error	DF	t-value	p-value
(Intercept: NOGP)	338.27	15.49	287	21.84	0
SOGP	62.39	28.08	73	2.22	0.0294
YNAL	-231.00	34.64	73	-6.67	0
WCPE	-139.36	23.86	73	-5.84	0
BBAL	-186.16	21.48	73	-8.67	0
WAAL	-153.23	19.60	73	-7.82	0
LMSA	-84.31	27.63	73	-3.05	0.0032
SOAL	-99.74	21.58	73	-4.62	0
AMAL	-121.94	21.91	73	-5.57	0

225

226 **Post-hoc Tukey test p-values:**

SPECIES	NOGP	SOGP	YNAL	WCPE	BBAL	WAAL	LMSA	SOAL	AMAL
NOGP									
SOGP	0.3756								
YNAL	<0.01	<0.01							
WCPE	<0.01	<0.01	0.1965						
BBAL	<0.01	<0.01	0.9254	0.5311					
WAAL	<0.01	<0.01	0.3037	0.9993	0.7197				
LMSA	0.0538	<0.01	<0.01	0.6084	<0.01	0.1498			
SOAL	<0.01	<0.01	<0.01	0.7451	<0.01	0.1133	0.9997		
AMAL	<0.01	<0.01	0.04	0.9982	0.0643	0.796	0.906	0.9817	

227 P < 0.05 are highlighted in dark cream, 0.05 < P < 0.1 are highlighted in light cream colour to highlight

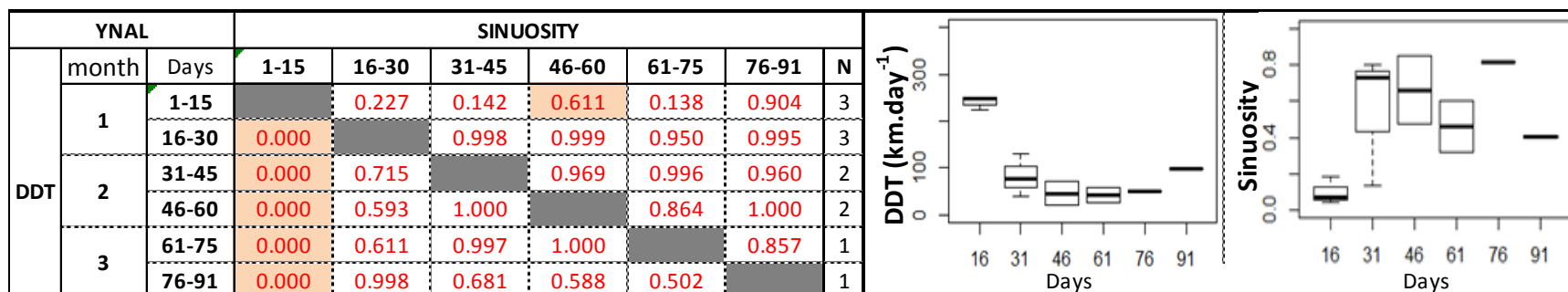
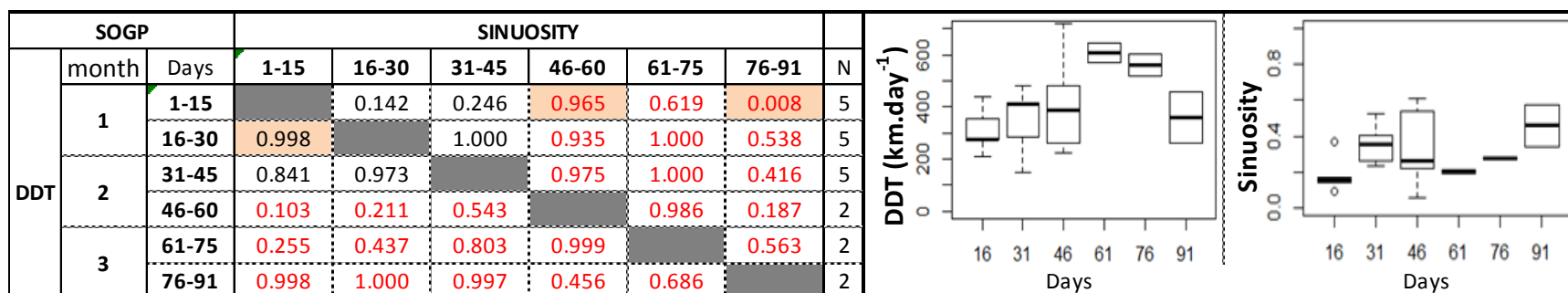
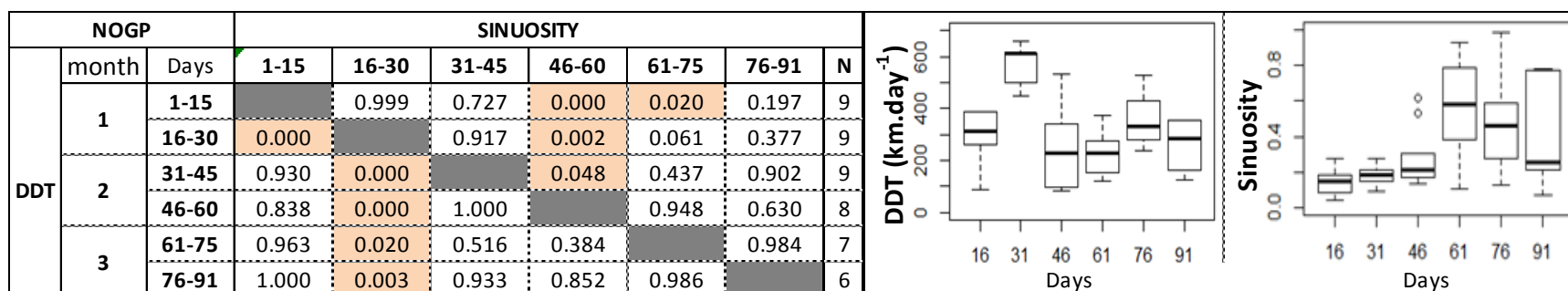
228 the tendency. Note that the YNAL sample is too small to give relevant results.

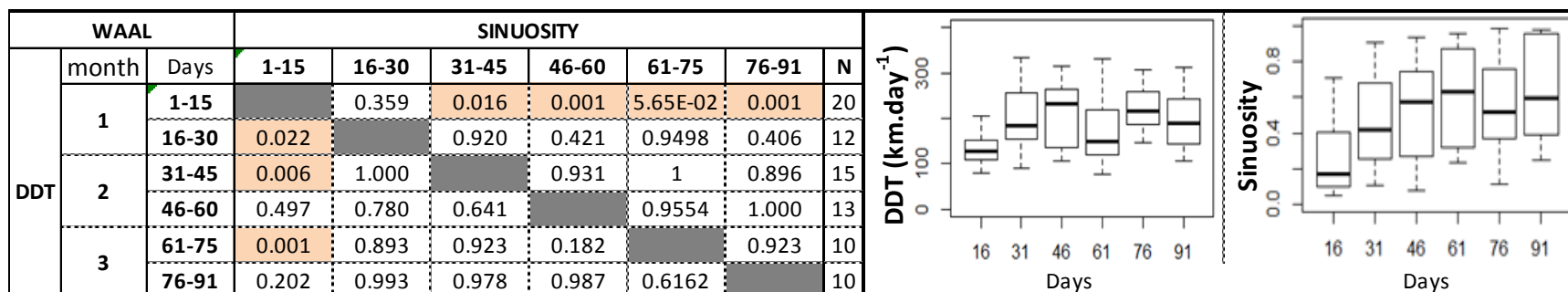
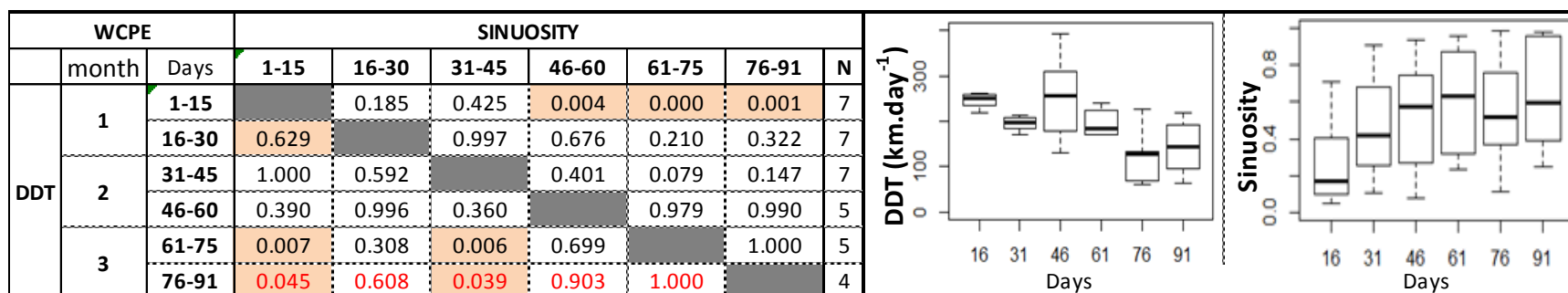
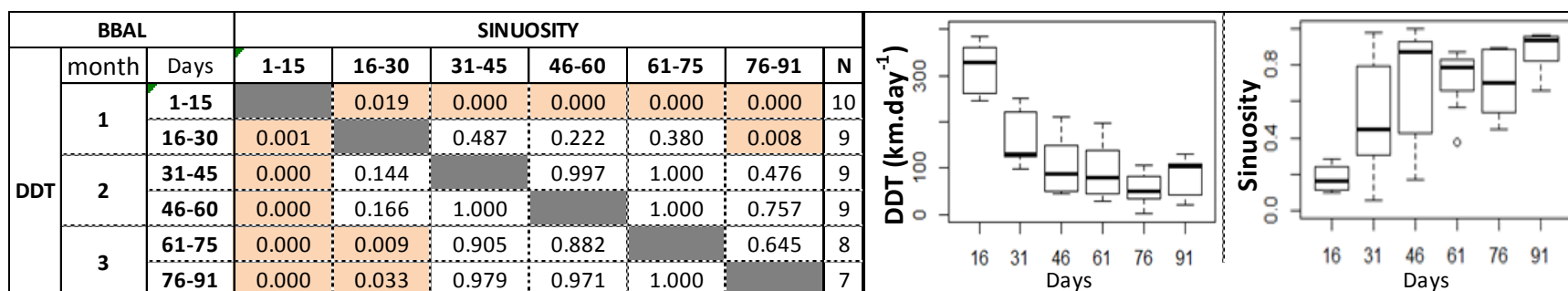
229 **Contrasting movement strategies among juvenile albatrosses and petrels**

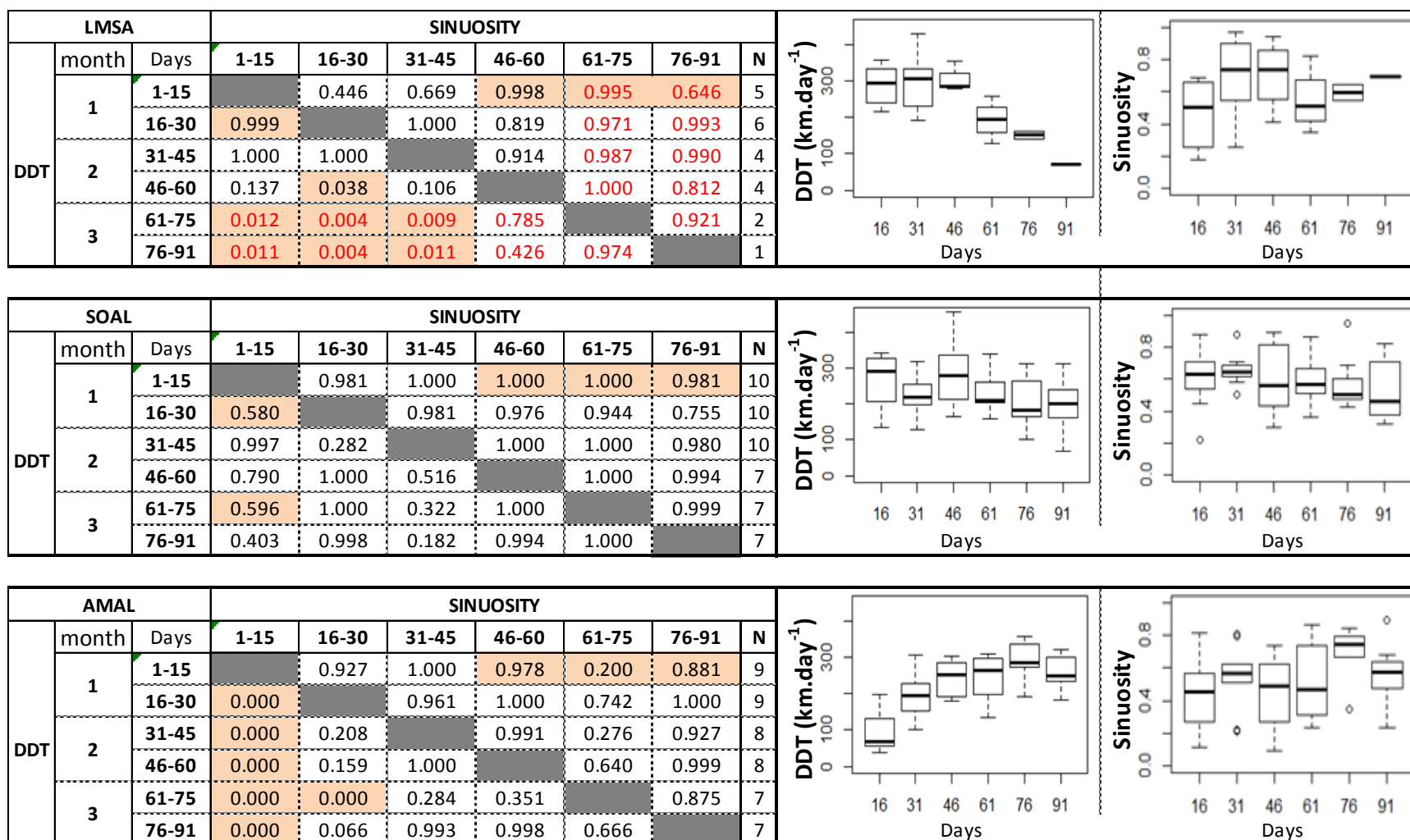
230 Sophie de Grissac* ^{a,b}, Luca Börger ^c, Audrey Guitteaud ^a and Henri Weimerskirch ^{a,b}

231 **Supplementary Table 2. Tukey tests outputs for temporal variation within species in sinuosity and daily**
232 **distance travelled.**

233
234 P-value tables of pairwise comparisons between time-periods of 15 days resulting from linear mixed models and post-hoc Tukey test.
235 For each species, the upper part of the table compares sinuosity between time-periods and the lower part of the table compares daily
236 distance travelled (DDT) between time-periods. $P < 0.05$ (significant effect) are highlighted in dark cream colour. N is the number of
237 individuals for each period. Red text means that the p-value is not relevant and/or prior modelling assumptions were not met due to
238 sample size.







Contrasting movement strategies among juvenile albatrosses and petrels

Sophie de Grissac* ^{a,b}, Luca Börger ^c, Audrey Guitteaud ^a and Henri Weimerskirch ^{a,b}

Supplementary Table.3. Distance to colony: comparison between species

Linear mixed model results with northern giant petrel (NOGP) as intercept:

Model: $\log(\text{Range}_{1\text{month}}) \sim \text{species} + \text{random} = \sim 1 \mid \text{individual}$

SPECIES	Value	Std.Error	DF	t-value	p-value
(Intercept: NOGP)	9.33	0.136	61	68.60	0
SOGP	-0.40	0.228	61	-1.76	0.0835
YNAL	-1.02	0.272	61	-3.76	0.0004
WCPE	-1.38	0.206	61	-6.70	0
BBAL	-0.76	0.192	61	-3.95	0.0002
WAAL	-1.71	0.180	61	-9.51	0
LMSA	-1.59	0.215	61	-7.41	0
SOAL	-1.71	0.187	61	-9.10	0
AMAL	-2.04	0.192	61	-10.60	0

The response variable, i.e. the maximum distance to colony reach during the first month, was log-transformed to meet the model assumptions.

Supplementary Fig. 2. Juveniles' habitat characterisation.

Boxplot of bathymetry (a), SST (a) and Chlorophyll *a* (c) along the tracks of juveniles of the nine species with median (bold line), interquartile range (boxes), dispersion (vertical lines) and outliers (points). Red lines and stars indicate Tukey test pairwise comparisons $P < 0.01$ (***) or $P < 0.05$ (**) between species.

