



Analysis of stable isotope ratios in blood of tracked wandering albatrosses fails to distinguish a $\delta^{13}\text{C}$ gradient within their winter foraging areas in the southwest Atlantic Ocean



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Complete List of Authors:	Ceia, Filipe; MARE - Marine and Environmental Sciences Centre, Department of Life Sciences Ramos, Jaime; MARE - Marine and Environmental Sciences Centre, Department of Life Sciences Phillips, Richard; British Antarctic Survey, Cherel, Yves; CEBC, Jones, Dan; British Antarctic Survey, Vieira, Rui; MARE - Marine and Environmental Sciences Centre, Xavier, José; British Antarctic Survey,
Keywords:	Diomedea exulans, Isoscapes, Oceanic front, Seabird, South Georgia
Abstract:	<p>RATIONALE: The main limitation of isotopic tracking for inferring distribution is the lack of detailed reference maps of the isotopic landscape (i.e. isoscapes) in the marine environment. Here, we attempt to map the marine $\delta^{13}\text{C}$ isoscape for the southwestern sector of the Atlantic Ocean, and assess any temporal variation using the wandering albatross as a model species.</p> <p>METHODS: Tracking data and blood and diet samples were collected monthly from wandering albatrosses rearing chicks at Bird Island, South Georgia, during the austral winter between May and October 2009. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values were measured by mass spectrometry in plasma and blood cells, and related to highly accurate data on individual movements and feeding activity obtained using three types of device: GPS, activity (immersion) loggers and stomach temperature probes.</p> <p>RESULTS: The tracked birds foraged in waters to the north or northwest of South Georgia, including the Patagonian shelf-break, as far as 2000 km from the colony. The foraging region encompassed the two main fronts in the Southern Ocean (Polar and Subantarctic fronts). $\delta^{13}\text{C}$ values varied by only 2.1 ‰ in plasma and 2.5 ‰ in blood cells, and no relationships were found between $\delta^{13}\text{C}$ values in plasma, and mean latitude or longitude of landings or feeding events of each individual.</p> <p>CONCLUSIONS: The failure to distinguish a major biogeographic gradient in $\delta^{13}\text{C}$ values suggest that $\delta^{13}\text{C}$ values in the south Atlantic Ocean are fairly homogenous. There was no substantial variation among months</p>

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	either in $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values of plasma or blood cells of tracked birds. As birds did not show a significant change in diet composition or foraging areas during the study period, these results provide no evidence for major temporal variation in stable isotope ratios in consumer tissues, or in the regional marine isoscape in the austral winter of 2009.

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1 **Analysis of stable isotope ratios in blood of**
2 **tracked wandering albatrosses fails to distinguish**
3 **a $\delta^{13}\text{C}$ gradient within their winter foraging areas**
4 **in the southwest Atlantic Ocean**

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6 Filipe R. Ceia^{1,*}, Jaime A. Ramos¹, Richard A. Phillips², Yves Cherel³, Daniel C.
7 Jones², Rui P. Vieira^{1,4,5}, José C. Xavier^{1,2}

8
9 ¹ MARE - Marine and Environmental Sciences Centre, Department of Life Sciences,
10 Universidade de Coimbra, 3004-517 Coimbra. Portugal

11 ² British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley
12 Road, Cambridge CB3 0ET, United Kingdom

13 ³ Centre d'Etudes Biologiques de Chizé, UPR 7372 du CNRS-Université de La Rochelle,
14 79360 Villiers-en-Bois, France

15 ⁴ Departamento de Biologia & CESAM, Universidade de Aveiro, Campus Universitário de
16 Santiago, 3810-193, Aveiro, Portugal

17 ⁵ Ocean and Earth Science, National Oceanography Centre, Southampton, European Way,
18 Southampton SO14 3ZH, United Kingdom

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20
21 * Corresponding author: Filipe Rafael Ceia

22 E-mail address: ceiafilipe@zoo.uc.pt

23 Telephone: +351 239 836 386

24 Fax: +351 239 823 603

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28 **Short title: Spatiotemporal isotopic variation in southwestern Atlantic waters**

30 **ABSTRACT**

31 **RATIONALE:** The main limitation of isotopic tracking for inferring distribution is the
32 lack of detailed reference maps of the isotopic landscape (i.e. isoscapes) in the marine
33 environment. Here, we attempt to map the marine $\delta^{13}\text{C}$ isoscape for the southwestern
34 sector of the Atlantic Ocean, and assess any temporal variation using the wandering
35 albatross as a model species.

36 **METHODS:** Tracking data and blood and diet samples were collected monthly from
37 wandering albatrosses rearing chicks at Bird Island, South Georgia, during the austral
38 winter between May and October 2009. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values were measured by mass
39 spectrometry in plasma and blood cells, and related to highly accurate data on individual
40 movements and feeding activity obtained using three types of device: GPS, activity
41 (immersion) loggers and stomach temperature probes.

42 **RESULTS:** The tracked birds foraged in waters to the north or northwest of South
43 Georgia, including the Patagonian shelf-break, as far as 2000 km from the colony. The
44 foraging region encompassed the two main fronts in the Southern Ocean (Polar and
45 Subantarctic fronts). $\delta^{13}\text{C}$ values varied by only 2.1 ‰ in plasma and 2.5 ‰ in blood
46 cells, and no relationships were found between $\delta^{13}\text{C}$ values in plasma, and mean latitude
47 or longitude of landings or feeding events of each individual.

48 **CONCLUSIONS:** The failure to distinguish a major biogeographic gradient in $\delta^{13}\text{C}$
49 values suggest that $\delta^{13}\text{C}$ values in the south Atlantic Ocean are fairly homogenous.
50 There was no substantial variation among months either in $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values of
51 plasma or blood cells of tracked birds. As birds did not show a significant change in diet
52 composition or foraging areas during the study period, these results provide no evidence
53 for major temporal variation in stable isotope ratios in consumer tissues, or in the
54 regional marine isoscape in the austral winter of 2009.

55 **Keywords:** *Diomedea exulans*; Isoscapes; Oceanic front; Seabird; South Georgia

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57 INTRODUCTION

58 The study of movements of marine wildlife is crucial for the conservation and
59 sustainable use of marine resources. Stable isotope analysis (SIA) provides a novel and
60 powerful tool for tracing animal movements because by analysing the appropriate
61 tissues we can link isotopic information to specific geographic areas, and hence
62 determine foraging areas of individuals.^[1,2] A prerequisite of isotopic tracking is the
63 identification and validation of isotopic geographic gradients (i.e. isoscapes) in marine
64 environments that can be used to improve our understanding of the foraging ecology
65 (distribution, trophic level and diet) of predators.^[3] There is a great deal of interest in
66 the mapping of marine isoscapes, as their limited availability reduces the inferences that
67 can be drawn from isotopic approaches.^[4]

68 Although there is a general lack of observational data on spatial isotopic
69 variability within the marine realm,^[5] previous studies have nevertheless been able to
70 detect broad latitudinal gradients from the tropics to the poles in carbon isotope ratios
71 (i.e. in $\delta^{13}\text{C}$) at the base of the food web (i.e. in plankton) mirroring those in particulate
72 organic matter.^[6,7] Typically, pelagic ecosystems at higher latitudes have much lower
73 $\delta^{13}\text{C}$ values than at lower latitudes. This broad $\delta^{13}\text{C}$ latitudinal gradient in baseline
74 values from polar to equatorial waters, is propagated through the food chain up to
75 marine top predators, such as seabirds.^[2] As $\delta^{13}\text{C}$ values vary little up the food chain,
76 the carbon isotope ratio typically reflects the consumer's foraging habitat (i.e. carbon
77 source), which is largely influenced by latitude in pelagic ecosystems, and between
78 inshore and offshore environments.^[8-11] On the other hand, stable isotope ratios of
79 nitrogen (i.e. $\delta^{15}\text{N}$) mainly reflect the consumer's trophic position, as there is a stepwise
80 enrichment of ^{15}N between prey and predators.^[9,12,13] Since isotopic patterns in food-
81 webs can differ spatially, information on residency periods and movement patterns can
82 be acquired by measuring isotope ratios in consumer tissues such as blood and keratin-
83 based tissues that can frequently be sampled in the field with minimal disturbance or
84 other impacts.^[3,14] In this context, stable isotopes are being used increasingly to study
85 spatial ecology as they have the advantage that the individual need be sampled only
86 once, whereas many electronic tracking devices need to be deployed and the animal
87 later recaptured for data retrieval.^[15] Although isoscapes do not provide the fine-spatial
88 scale detail obtained with electronic devices, they improve our understanding of animal

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3 89 movement within the marine realm, and support marine spatial planning and
4 90 conservation efforts.^[5]
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7 91 The southwestern sector of the Atlantic Ocean includes two main oceanic
8 92 fronts, namely the Antarctic Polar Front (PF) and the Subantarctic Front (SAF), which
9 93 in this region are steered into meandering paths by the Patagonian Shelf and by the
10 94 complex bathymetry of the Scotia Sea.^[16,17] The region from 40°S to 62°S is
11 95 characterized by a noticeable decline in $\delta^{13}\text{C}$ values with latitude at the base of the food
12 96 web, particularly south of South Georgia and in the Drake Passage from 53°S to 62°S,
13 97 where values decrease from approximately -23 to -30 ‰, respectively.^[6,7,18] In contrast,
14 98 $\delta^{13}\text{C}$ values are more homogeneous in waters from the North Scotia Ridge (which
15 99 extends from South Georgia to the Patagonian Shelf) north to the subtropics, i.e., 40-
16 100 53°S and 38-60°W. This region encompasses the two main oceanic fronts, but the
17 101 latitudinal and longitudinal gradients in $\delta^{13}\text{C}$ are indistinct, with values ranging from -
18 102 19 to -23 ‰ at the base of the food web.^[6,18] Few studies have validated isoscapes for
19 103 top predators in the Southern Ocean^[3,11] and, to our knowledge, none has done so using
20 104 a combination of stable isotope analyses, highly accurate GPS tracking, and data on
21 105 timing of feeding events for the Atlantic sector of the Southern Ocean during the austral
22 106 winter. In addition, knowledge of temporal variation in isotopic ratios is essential to
23 107 determine the robustness of isotopic tools^[19], but is still limited for taxa in pelagic
24 108 ecosystems.^[1]
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38 109 The wandering albatross (*Diomedea exulans*) was chosen as a model top
39 110 predator species because these are large animals that forage over vast areas of the
40 111 Southern Ocean during the breeding season.^[20] Wide-ranging seabirds might be very
41 112 good samplers for the construction and validation of marine isoscapes from local to
42 113 continental scales.^[3] Wandering albatrosses from South Georgia are known to forage
43 114 between 28°S (off Brazil) and 63°S (Antarctic Peninsula shelf) and from 19°W (off
44 115 Tristan da Cunha) to 68°W (Patagonian Shelf and oceanic waters south of Cape Horn)
45 116 during the chick-rearing period, which includes the austral winter.^[20] Thus, given their
46 117 wide geographical range, we expect a positive relationship between $\delta^{13}\text{C}$ values and
47 118 mean latitudes of foraging areas of tracked birds, given the positive $\delta^{13}\text{C}$ gradient at the
48 119 base of the food web in the region (from approximately -18 ‰ at 28°S to -30 ‰ at
49 120 63°S).^[18] The main objectives of this study are to: 1) validate the marine $\delta^{13}\text{C}$ isoscape
50 121 for top consumers in the southwest sector of the Atlantic Ocean during the austral
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3 122 winter, and 2) assess monthly differences (from May to October) in stable isotope ratios
4 123 (i.e. temporal variation).
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9 125 **EXPERIMENTAL**

10 126 **Fieldwork**

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14 127 Fieldwork was carried out on wandering albatrosses rearing chicks at Bird Island
15 128 (54°S 38°W), South Georgia, from May to October 2009 (austral late autumn to early
16 129 spring; hereafter termed the austral winter). Thirty-six breeding adults were fitted with
17 130 devices, but one bird returned only in January 2010, and so samples were available from
18 131 a total of 35 birds (see Table 1). Each individual bird was fitted simultaneously with a
19 132 GPS and activity (saltwater immersion) recorder (AR) and, when possible, a stomach
20 133 temperature probe (Table 1) (see Ceia et al.^[21] for detailed specifications on the
21 134 devices). The devices were removed and a blood sample (1 ml blood from the tarsal
22 135 vein) was collected at the end of the subsequent foraging trip. The trip duration of each
23 136 bird was recorded. Additionally, stomach contents were sampled by water-offloading
24 137 following Xavier et al.^[20] Capture, deployment or retrieval of devices, collection of
25 138 samples and release took 10–15 min. No birds were sampled more than once, nor a
26 139 sample taken from the partner of a previously sampled bird. The blood samples were
27 140 separated into plasma and blood cell fractions within 2–3 hours using a centrifuge (15
28 141 min at 3 000 rpm) and subsequently stored frozen until isotopic analysis.
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40 142 **Diet sampling**

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42 143 Food samples collected from each individual reflected recent prey ingestions.
43 144 Following Xavier et al.,^[20] regurgitates were separated into oil and solid mass and each
44 145 component (cephalopod, fish, crustacean and carrion) was weighed separately.
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48 146 **Stable isotope analysis (SIA)**

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51 147 We analysed $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in plasma and blood cells from each adult (N
52 148 = 35, Table 1). Although there is overlap in the synthesis of plasma and blood cells,
53 149 each tissue has a different turnover rate and therefore represents different timescales in
54 150 terms of diet integration. Plasma turnover rate is high, with a half-life of components of
55 151 up to one week, whereas the turnover rate of blood cells is typically slower, with a half-
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3 152 life of several weeks, and retaining information on diet in the 4-5 weeks prior to sample
4 153 collection in wandering albatrosses.^[22] Hence, the isotopic signature of plasma was
5 154 representative largely of diet during the single trip in which each bird was tracked
6 155 (mean trip duration \pm SD for the 35 birds = 6.5 ± 5.0 days).

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10 156 Samples were freeze-dried and homogenized prior to SIA. The low lipid level of
11 157 blood cells and of whole blood does not affect their $\delta^{13}\text{C}$ values, but the high and
12 158 varying lipid concentrations of plasma can result in depletion of ^{13}C .^[13,23] Hence, lipids
13 159 were removed from plasma but not blood cells using successive rinses in a 2:1
14 160 chloroform–methanol solution. The means \pm SD in C:N mass ratio of the blood cells
15 161 and delipidated plasma was 3.27 ± 0.07 and 3.37 ± 0.03 , respectively (N = 35 birds); no
16 162 monthly differences were found in C:N mass ratio for both tissues (see Table 2). The
17 163 values are thus below the 3.50 threshold which correspond to a low lipid concentration
18 164 in tissue.^[24]

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26 165 Nitrogen and carbon isotope ratios were determined by a continuous-flow
27 166 isotope ratio mass spectrometer (Delta V Advantage, Thermo Scientific, Bremen,
28 167 Germany) coupled to an elemental analyser (Flash EA1112, Thermo Scientific).
29 168 Approximately 0.3 mg of each sample was combusted in a tin cup for the simultaneous
30 169 determination of nitrogen and carbon isotope ratios. The results are presented in δ
31 170 notation as deviations from the standard references in parts per thousand (‰) according
32 171 to the following equation: $\delta X = [(R_{\text{sample}} / R_{\text{standard}}) - 1]$, where X represents ^{13}C or
33 172 ^{15}N and R_{sample} the ratios $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$, respectively. R_{standard} represents the
34 173 international reference standard Vienna PeeDee Belemnite (V-PDB) and atmospheric
35 174 nitrogen (AIR) is the standard for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, respectively. Replicate
36 175 measurements of internal laboratory standards (acetanilide STD: Thermo scientific—PN
37 176 338 36700) indicate precision <0.1 ‰ for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

177 **Tracking, activity (immersion) and stomach temperature probe analysis**

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179 All the 36 activity recorders were retrieved and downloaded successfully (one in
180 January 2010). The activity recorders check for saltwater immersion every 3 s,
181 recording every change of state from wet to dry, or *vice versa*, that lasts ≥ 6 s. GPS data
182 were obtained from 33 of the 36 loggers deployed, of which 27 recorded data during the
183 whole trip. Data from all birds with complete trips, and from two birds in which the
GPS recorded for $>84\%$ of the foraging trip, were included in analyses; the remaining

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3 184 four bird tracks were excluded because the GPS recorded positions for <55% of the trip.
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5 185 This resulted in a total of 29 birds with reliable GPS data (see Table 1). The GPS
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7 186 loggers (median error of <10 m) were set to record location every 20 min. GPS and
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9 187 activity (immersion) data were used simultaneously to determine latitude and longitude
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11 188 of landing events on the water that accounted >10 mins. between consecutive tracking
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13 189 points (i.e. 20 mins.), which was assumed to correspond to a feeding attempt. From the
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15 190 26 birds equipped with a stomach temperature probe (STP), a total of 23 were retrieved,
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17 191 22 of which downloaded successfully; data from 17 of these loggers were used in
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19 192 further analyses (Table 1). The data on temperature recorded every 20 s by the STPs
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21 193 were combined with GPS and activity (immersion) data to estimate the latitude and
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23 194 longitude of prey ingestions (feeding events). Changes in temperature <4 °C usually
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25 195 reflect ingestion of water or very small prey and were excluded from the analyses.^[25]
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27 196 There were highly significant positive Pearson correlations between mean latitude and
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29 197 longitude of attempted (from immersion data) and successful prey captures (from STP
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31 198 data) (latitude: $r = 0.96$, $F_{1,15} = 197.8$, $p \ll 0.001$; longitude: $r = 0.98$, $F_{1,15} = 430.8$, p
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33 199 $\ll 0.001$) indicating minor bias between mean geographic positions calculated using
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35 200 these two approaches. Hence, to maximise sample sizes (because STP data were
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37 201 unavailable for some individuals), we relate stable isotope ratios in blood to the mean
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39 202 location of prey capture attempts as well of prey ingestions by each individual.

203 **Data analysis**

204 Due to small sample sizes within each month, we used the non-parametric
205 Kruskal-Wallis test, followed by multiple comparisons, to examine differences between
206 months in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, diet composition, trip duration and mean positions
207 (latitude and longitude) of attempted and successful prey captures. According to
208 Boecklen et al.^[1] we considered two main sources of variation in isotopic values: diet
209 and trophic position. However, the properties of the consumer such as age, body size,
210 body condition, physiology among others, may also contribute to variation in isotopic
211 signatures, as secondary mechanistic factors.^[1,2] We checked for possible $\delta^{13}\text{C}$
212 biogeographic gradients using Pearson's correlation, to identify relationships between
213 the $\delta^{13}\text{C}$ values of plasma and mean foraging locations of each bird. In these analyses,
214 latitude and longitude data were \log_{10} -transformed to fit a normal distribution. We used
215 ArcGIS v.10.1 (ESRI, Redlands, CA, USA) to plot the distribution of the mean location
216 of prey capture attempts by each tracked bird, and used a natural neighbour

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3 217 interpolation in the Spatial Analyst Tool to model and visualize geographic gradients in
4 218 $\delta^{13}\text{C}$ values of plasma within the foraging area during the austral winter (Fig. 1).

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10 220 **RESULTS**

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12 221 Overall, $\delta^{13}\text{C}$ values for the 35 wandering albatrosses sampled from May to
13 222 October, i.e., throughout the austral winter, varied between -21.3 and -19.1 ‰ in
14 223 plasma, and between -21.2 and -18.7 ‰ in blood cells. $\delta^{15}\text{N}$ values ranged from 13.6 to
15 224 15.1 ‰ in plasma and from 13.5 to 14.7 ‰ in blood cells. We found no differences
16 225 between months (from May to October) in the mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of either
17 226 plasma or blood cells in all study birds, or if the analysis is limited to the 29 birds for
18 227 which GPS and immersion data were available, or just the 17 birds for which there were
19 228 usable data from all three kinds of device (Table 2).

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26 229 There was no significant effect of month on the mean duration of foraging trips
27 230 for the entire sample ($H_{5,35} = 6.1$, $p = 0.30$), nor the subsets of birds for which GPS and
28 231 immersion data were available ($H_{5,29} = 5.8$, $p = 0.33$) or those for which GPS,
29 232 immersion and STP data were obtained ($H_{3,17} = 1.4$, $p = 0.71$). Overall, the diet of the 35
30 233 birds sampled was composed mainly of fish (59.4 % by mass) and cephalopods (38.4
31 234 %), a small amount of carrion (2.2 %) and trace amounts of crustaceans (0.02 %).
32 235 Despite a decrease in the consumption of fish in September and October and a
33 236 consequent increase in the consumption of cephalopods during the same months, no
34 237 significant differences between months were observed in the proportions of each
35 238 category of prey either in samples from all birds, or just from those for which all three
36 239 types of tracking data were obtained (Table 2).

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45 240 All the 29 birds for which GPS data were obtained travelled north or northwest
46 241 of South Georgia during their foraging trips; mean latitude and longitude of all feeding
47 242 attempts (immersion events that lasted >10 mins.) on these trips were distributed from
48 243 40°S to 54°S and 37°W to 54°W, respectively. This region encompasses the two main
49 244 ocean fronts (PF and SAF), and the shelf that extends from South Georgia west to the
50 245 Burdwood Bank (Fig. 1). Depth varied from 100 to 6000 m at these locations. The
51 246 overall mean latitudes and longitudes did not differ significantly by month for
52 247 wandering albatrosses from which both GPS and activity data were obtained, although
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3 248 small differences were detected in latitude between September and May ($p = 0.043$),
4 249 and longitude between August and May ($p = 0.048$) (Table 2). No significant
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6 250 differences were found between months in the mean latitudes and longitudes of feeding
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8 251 (Table 2).

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10 252 No linear relationships were found between the $\delta^{13}\text{C}$ values of plasma and the
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12 253 mean latitude ($r = 0.08$, $F_{1,27} = 0.2$, $p = 0.66$) or longitude ($r = 0.34$, $F_{1,27} = 3.5$, $p = 0.07$)
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14 254 of feeding attempts of the 29 wandering albatrosses from which GPS and immersion
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16 255 data were obtained. Similarly, no relationships were found between the $\delta^{13}\text{C}$ values and
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18 256 the mean latitude ($r = 0.11$, $F_{1,15} = 0.2$, $p = 0.68$) or longitude ($r = 0.20$, $F_{1,15} = 0.6$, $p =$
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20 257 0.45) of feeding events based on the STP data.

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23 24 259 **DISCUSSION**

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26 260 During this study, wandering albatrosses from Bird Island foraged exclusively to
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28 261 the north or northwest of the colony, in the vicinity of South Georgia or Shag Rocks, or
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30 262 towards the Patagonian Shelf. This region encompasses the Antarctic Polar Front (PF),
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32 263 the Subantarctic Front (SAF) and the northern extension of the Subantarctic Front
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34 264 (SAF_N), and is consistent with the foraging distribution identified in past tracking
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36 265 studies of wandering albatrosses breeding at Bird Island, although of considerably
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38 266 smaller range.^[20] Based on a previous analysis of the stable isotope data in this paper,
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40 267 but with a different focus, Ceia et al.^[21] demonstrated that the tracked birds showed high
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42 268 short-term (within season) consistency in foraging habitat (i.e. carbon source) and
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44 269 trophic level. It is therefore probable that these individual wandering albatrosses tended
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46 270 to concentrate their foraging in particular areas on consecutive trips during the chick-
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48 271 rearing period.

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50 272 No relationships were found between $\delta^{13}\text{C}$ values and mean latitudes or
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52 273 longitudes of the individual trips, suggesting there was no consistent biogeographic
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54 274 gradient in $\delta^{13}\text{C}$ values in waters north and northwest of South Georgia to *ca.* 40° S.
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56 275 Overall $\delta^{13}\text{C}$ values in the blood of the sampled wandering albatrosses showed limited
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58 276 variation (by 2.1 ‰ in plasma and 2.5 ‰ in blood cells) despite the differences in
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60 277 individual foraging areas, which were across a region that encompasses two main
278 278 oceanic fronts (Fig. 1). These results thus contrast with the larger range of $\delta^{13}\text{C}$ values (-

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3 279 24 to -19 ‰) and their positive relationship with foraging latitudes for the same species
4 280 at approximately the same latitudes, and including the same oceanic fronts, in the south
5 281 Indian Ocean from January to March 2008 (i.e. during the austral summer).^[3] During
6 282 this study, the lowest $\delta^{13}\text{C}$ values (around -21 ‰) were observed in birds that had fed
7 283 near the confluence of the Antarctic Polar Front (PF) and the Subantarctic Front (SAF),
8 284 in the eastern extent of the overall foraging area, *ca.*500-600 km north of the study site
9 285 (Fig. 1). The particularly complex oceanography of this region results from variable
10 286 bathymetry, intense eddy formation and meandering of the ocean fronts and currents,^[26]
11 287 such that these are poorly associated with latitude.^[16,17,27] However, isotope data
12 288 (particularly $\delta^{13}\text{C}$) are broadly indicative of water mass and not of latitude by itself.^[11]
13 289 As a result, the lack of consistency in the latitudinal stratification of the different water
14 290 masses confuses the stable isotope signals and presumably weakens the isotopic
15 291 gradient,^[28] especially during the winter when the ocean is more agitated. According to
16 292 Graham et al.^[6] and Quillfeldt et al.,^[18] this region of the southwest Atlantic is
17 293 characterized by much higher $\delta^{13}\text{C}$ values at the base of the food web, with an indistinct
18 294 isotopic gradient, whereas waters south of the Antarctic Polar Front show a clearer
19 295 decline in $\delta^{13}\text{C}$ values with latitude. Although the observed latitudinal and longitudinal
20 296 range of the tracked birds (i.e. from 40°S to 54°S and from 37°W to 54°W) was smaller
21 297 than expected, the range of the observed $\delta^{13}\text{C}$ values in both plasma and blood cells of
22 298 sampled birds (Table 2) are consistent with reported values for organisms at the base of
23 299 the food web for this region (from -19 to -23 ‰),^[6,7,18] considering an expected
24 300 enrichment between the base of the food web and top predators in ^{13}C of about 1 ‰.^[29]
25 301 This region shows little variation in carbon stable isotope values at the base of the food
26 302 web and our results also suggest fairly homogeneous $\delta^{13}\text{C}$ values at the level of a top
27 303 consumer around South Georgia and up to a distance of approximately 2000 km
28 304 northwest, towards the Patagonian Shelf. However, only part of the southwest Atlantic
29 305 was ‘sampled’ in comparison to the whole region foreseen, which may have weakened
30 306 and masked the biogeographic gradients in $\delta^{13}\text{C}$ values expected for the region, as some
31 307 studies of stable isotope analysis in lower trophic-level organisms suggest.^[7,30] As the
32 308 tracked wandering albatrosses did not travel south of the colony, we were unable to map
33 309 the $\delta^{13}\text{C}$ isoscape in Antarctic waters towards the Antarctic Peninsula, where a positive
34 310 relationship between $\delta^{13}\text{C}$ values and latitude would be expected,^[6,7,18] as, in fact,
35 311 seems to occur in the Southern Ocean in general.^[3,8,11]

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3 312 There was no consistent effect of month on stable isotope ratios in plasma or
4 313 blood cells of the sampled birds, nor on diet composition or the mean latitudes and
5 314 longitudes of feeding areas, which suggests that baseline isotope ratios showed little
6 315 variation during the study period (i.e. austral winter 2009). Currently, there is a large
7 316 gap in our knowledge of temporal isotopic variation worldwide.^[1] However, the $\delta^{13}\text{C}$
8 317 and $\delta^{15}\text{N}$ values of top consumers integrate those of multiple prey (fish and squid) and
9 318 may not necessarily reflect the lack of such variation at the base of the food web. Few
10 319 previous studies have incorporated data on temporal variation (within and between
11 320 years) in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (but see Quillfeldt et al.^[31]), although this is potentially
12 321 an important reason for variation between top consumers of different species or
13 322 populations in pelagic ecosystems of the Southern Ocean,^[9,32] and the North Atlantic.^[33]
14 323 Several authors suggested that overall variation in stable isotope values measured in
15 324 predator tissues is more likely to be related to variation in their diets and foraging
16 325 distributions,^[34–36] but the temporal shifts and biogeographical trends in baseline isotope
17 326 ratios should be considered in order to avoid misinterpretations in future studies as
18 327 suggested by Quillfeldt et al.^[31] Baseline and lower trophic level organisms may show
19 328 substantial spatiotemporal isotopic heterogeneity^[7,30,31] and local enrichment in ^{13}C in
20 329 phytoplankton during periods of elevated primary productivity will influence isotopic
21 330 values of upper trophic level organisms.^[37] Our results suggest that there is limited
22 331 temporal variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of top consumers in our study region during
23 332 the austral winter of 2009, but of course, variation in isotope ratios could be more
24 333 substantial in the long-term.

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40 334 Although wide-ranging seabirds, and particularly wandering albatrosses, could
41 335 be powerful samplers for the validation of marine isoscapes,^[3] it should be noticed that
42 336 seabirds may present some limitations to infer about spatiotemporal variation in marine
43 337 isoscapes. This is because wandering albatrosses, and seabirds in general, are apex
44 338 predators that feed on higher trophic level prey that integrate (and then buffer)
45 339 spatiotemporal isotopic variations (especially at the base of the food web). The general
46 340 limitations are (i) that wandering albatrosses feed at multiple locations along the track
47 341 and on prey of different species and size and potentially of widely-differing isotope
48 342 signatures, and (ii) these prey themselves move both horizontally and vertically in the
49 343 water column, so their isotope ratios will not necessarily reflect $\delta^{13}\text{C}$ values in the ocean
50 344 at the point of capture. In addition, (iii) ingestion of fisheries discards (from benthic
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3 345 discards or bait that could be from anywhere originally) can complicate matters even
4 346 further.^[38] On the other hand, particular caveats of this study may bias the overall
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6 347 results because (iv) the overall distribution of all the single mean locations from each
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8 348 bird provides a relatively poor overall spatiotemporal coverage, with only a few
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10 349 locations in the northwest and during June and October, and (v) plasma turnover rate is
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12 350 up to one week such that if the bird fitted with a GPS returns within a few days, it could
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14 351 be possible to still reflect some isotopic signal from the previous foraging trip (although
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16 352 birds showed a high individual consistency in the foraging niche, particularly over the
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18 353 short time-period).^[21] Giving all these limitations, we can argue that for this region the
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20 354 gradient was likely to be weak or indiscernible at the top consumer level, resulting in
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22 355 fairly homogeneous $\delta^{13}\text{C}$ values, in contrast with the results in the southern Indian
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24 356 Ocean.^[3] However, this may not be true for organisms at lower-trophic levels, although
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26 357 the complex oceanographic features of this region (compared with the southern Indian
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28 358 Ocean with better stratified frontal systems and less eddies and retroflexion of currents)
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30 359 suggests that the issue is more of changes in $\delta^{13}\text{C}$ values with water mass, rather than
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32 360 latitude.

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362 **Conclusions**

363 Our study examines the $\delta^{13}\text{C}$ isoscape for a top consumer, the wandering
364 albatross, in the southwest Atlantic Ocean north of South Georgia during the austral
365 winter (May to October 2009). Although this region includes the two main oceanic
366 fronts (Polar and Subantarctic fronts), our results suggest a fairly homogeneous $\delta^{13}\text{C}$
367 isoscape at the level of a top consumer, in comparison with the more pronounced
368 isotopic gradient with latitude that occurs further south, as indicated in previous studies.
369 We did not find any evidence of major temporal variation in stable isotope values in
370 blood of the tracked birds during the study period, suggesting a consistent pattern
371 during the winter season in this region at the level of a top predator. However, isoscapes
372 may vary from one year/season to another and assumptions about baseline isotope
373 values from different water masses cannot automatically be extrapolated from one
374 geographic area to another broadly similar area. Future studies should attempt to
375 validate isoscapes in different marine environments and assess temporal isotopic
376 variation across larger spatiotemporal scales at both baseline and higher trophic levels.

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3 377 Once validated, isoscapes can provide valuable insights into the distribution of many
4 378 marine species that can be sampled at different levels of the foodweb, with applications
5 379 that range from conservation management, e.g., identification of biodiversity hotspots,
6 380 to addressing potential conflicts with commercial interests such as fishing, particularly
7 381 in regions that are as vulnerable as those around Antarctica.
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515 **TABLES**

516 **Table 1.** Number of GPS, AR (activity (immersion) recorders) and STP (stomach
 517 temperature probes) loggers deployed, retrieved and downloaded successfully, and
 518 blood and diet samples obtained, from wandering albatrosses breeding at Bird Island by
 519 month from May to October 2009.

2009	May	June	July	August	September	October	Total
Deployments							
GPS	6	6	6	8	6	4	36
AR	6	6	6	8	6	4	36
STP	6	6	6	8	0	0	26
Retrievals							
GPS	6	4	6	8	6	3	33
AR	6	6	6	8	6	4	36
STP	6	6	4	7	-	-	23
Downloaded successfully							
GPS	6	4	6	8	6	3	33
AR	6	6	6	8	6	4	36
STP	6	6	3	7	-	-	22
Combined devices with successful data							
GPS and AR	6	3	6	6	5	3	29
GPS, AR and STP	6	3	3	5	-	-	17
Tissue samples for stable isotope analyses and diet samples							
Plasma	6	6	6	8	6	3	35
Blood cells	6	6	6	8	6	3	35
Regurgitates	6	6	6	8	6	3	35

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Table 2. Comparison of foraging parameters (trip duration, mean latitude and longitude), stable isotope values ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and C:N mass ratio in blood cells and delipidated plasma, and diet composition (proportion by mass of fish, cephalopods, crustaceans and carrion, based on the stomach contents) of breeding wandering albatrosses sampled at Bird Island, South Georgia, from May to October 2009. Values are means \pm SD. Identical superscript letters indicate significant differences between months (multiple comparisons). Stable isotope analysis (SIA); activity (immersion) recorders (AR); stomach temperature probes (STP).

2009							Kruskal-Wallis test	
A. All birds (n=35)	May (n=6)	June (n=6)	July (n=6)	August (n=8)	September (n=6)	October (n=3)	$H_{(5,35)}$	P
Trip duration (days)	3.2 \pm 1.4	6.3 \pm 4.9	5.7 \pm 3.1	6.0 \pm 5.3	11.3 \pm 6.5	6.5 \pm 5.1	6.1	0.30
SIA								
Plasma $\delta^{13}\text{C}$ (‰)	-19.9 \pm 0.6	-20.2 \pm 0.6	-20.5 \pm 0.4	-19.7 \pm 0.5	-19.9 \pm 0.6	-20.1 \pm 0.8	7.0	0.22
Plasma $\delta^{15}\text{N}$ (‰)	14.5 \pm 0.5	14.4 \pm 0.4	14.2 \pm 0.5	14.5 \pm 0.4	14.1 \pm 0.4	14.2 \pm 0.5	4.5	0.47
Plasma C:N mass ratio	3.37 \pm 0.02	3.40 \pm 0.04	3.35 \pm 0.02	3.36 \pm 0.02	3.38 \pm 0.05	3.35 \pm 0.02	7.9	0.16
Blood cells $\delta^{13}\text{C}$ (‰)	-20.4 \pm 0.6	-20.2 \pm 0.3	-20.3 \pm 0.3	-20.1 \pm 0.3	-19.8 \pm 0.6	-19.7 \pm 0.9	3.6	0.61
Blood cells $\delta^{15}\text{N}$ (‰)	14.0 \pm 0.2	14.1 \pm 0.3	14.1 \pm 0.3	14.1 \pm 0.4	14.1 \pm 0.3	14.3 \pm 0.4	2.2	0.82
Blood cells C:N mass ratio	3.27 \pm 0.03	3.26 \pm 0.04	3.27 \pm 0.05	3.31 \pm 0.14	3.26 \pm 0.04	3.25 \pm 0.05	1.2	0.95
Diet								
Fish (% by mass)	63.0 \pm 41.5	55.2 \pm 48.3	63.5 \pm 49.6	64.2 \pm 37.9	29.1 \pm 38.3	1.4 \pm 2.3	7.7	0.17
Cephalopods (% by mass)	34.0 \pm 42.4	44.8 \pm 48.3	36.5 \pm 49.6	22.8 \pm 33.2	70.9 \pm 38.3	90.1 \pm 13.8	7.0	0.22
Crustaceans (% by mass)	0.3 \pm 0.7	0	0	0	<0.1	0	4.0	0.56
Carrion (% by mass)	2.7 \pm 6.6	0	0	13.0 \pm 28.1	<0.1	8.5 \pm 14.8	5.6	0.34
B. GPS and AR (n=29)	May (n=6)	June (n=3)	July (n=6)	August (n=6)	September (n=5)	October (n=3)	$H_{(5,29)}$	P
Trip duration (days)	3.2 \pm 1.4	5.4 \pm 7.3	5.7 \pm 3.1	4.8 \pm 4.6	10.7 \pm 7.1	6.5 \pm 5.1	5.8	0.33
Latitude in ° (of feeding attempts)	-53.6 \pm 0.4 ^a	-49.1 \pm 8.0	-50.2 \pm 2.1	-49.7 \pm 3.6	-44.8 \pm 6.0 ^a	-50.2 \pm 2.4	9.7	0.08
Longitude in ° (of feeding attempts)	-45.4 \pm 5.3 ^a	-44.0 \pm 8.8	-42.2 \pm 5.7	-38.8 \pm 1.1 ^a	-44.1 \pm 4.3	-41.6 \pm 5.4	10.0	0.07
SIA								
Plasma $\delta^{13}\text{C}$ (‰)	-19.9 \pm 0.6	-20.4 \pm 0.8	-20.5 \pm 0.4	-19.8 \pm 0.5	-19.8 \pm 0.5	-20.1 \pm 0.8	5.7	0.33
Plasma $\delta^{15}\text{N}$ (‰)	14.5 \pm 0.5	14.4 \pm 0.6	14.2 \pm 0.5	14.4 \pm 0.5	14.2 \pm 0.3	14.2 \pm 0.5	2.4	0.79
Blood cells $\delta^{13}\text{C}$ (‰)	-20.4 \pm 0.6	-20.3 \pm 0.4	-20.3 \pm 0.3	-20.3 \pm 0.1	-19.6 \pm 0.5	-19.7 \pm 0.9	5.5	0.36
Blood cells $\delta^{15}\text{N}$ (‰)	14.0 \pm 0.2	14.0 \pm 0.5	14.1 \pm 0.3	14.0 \pm 0.4	14.2 \pm 0.2	14.3 \pm 0.4	2.8	0.73
Diet								
Fish (% by mass)	63.0 \pm 41.5	67.3 \pm 56.7	63.5 \pm 49.6	80.7 \pm 26.3	34.9 \pm 39.7	1.4 \pm 2.3	8.0	0.16
Cephalopods (% by mass)	34.0 \pm 42.4	32.7 \pm 56.7	36.5 \pm 49.6	15.4 \pm 27.0	65.1 \pm 39.7	90.1 \pm 13.8	7.3	0.20
Crustaceans (% by mass)	0.3 \pm 0.7	0	0	0	<0.1	0	3.4	0.64

Carrion (% by mass)	2.7 ± 6.6	0	0	3.9 ± 7.5	<0.1	8.5 ± 14.8	3.7	0.59
C. GPS, AR and STP (n=17)	May (n=6)	June (n=3)	July (n=3)	August (n=5)	September (n=0)	October (n=0)	H _(3,17)	P
Trip duration (days)	3.2 ± 1.4	5.4 ± 7.3	4.9 ± 2.6	3.6 ± 3.7			1.4	0.71
Latitude in ° (of prey ingestions)	-53.6 ± 0.3	-50.0 ± 6.4	-50.5 ± 2.7	-49.6 ± 4.2			3.2	0.36
Longitude in ° (of prey ingestions)	-44.2 ± 4.3	-43.3 ± 7.4	-44.6 ± 6.1	-39.2 ± 1.3			6.1	0.10
SIA								
Plasma δ ¹³ C (‰)	-19.9 ± 0.6	-20.4 ± 0.8	-20.4 ± 0.3	-19.7 ± 0.4			4.5	0.21
Plasma δ ¹⁵ N (‰)	14.5 ± 0.5	14.4 ± 0.6	14.3 ± 0.5	14.5 ± 0.5			0.8	0.84
Blood cells δ ¹³ C (‰)	-20.4 ± 0.6	-20.3 ± 0.4	-20.3 ± 0.2	-20.2 ± 0.1			0.8	0.85
Blood cells δ ¹⁵ N (‰)	14.0 ± 0.2	14.0 ± 0.5	14.0 ± 0.2	14.1 ± 0.4			0.9	0.83
Diet								
Fish (% by mass)	63.0 ± 41.5	67.3 ± 56.7	60.8 ± 53.4	80.9 ± 29.4			1.4	0.72
Cephalopods (% by mass)	34.0 ± 42.4	32.7 ± 56.7	39.2 ± 53.4	18.2 ± 29.2			1.2	0.76
Crustaceans (% by mass)	0.3 ± 0.7	0	0	0			1.8	0.61
Carrion (% by mass)	2.7 ± 6.6	0	0	0.9 ± 1.9			1.2	0.76

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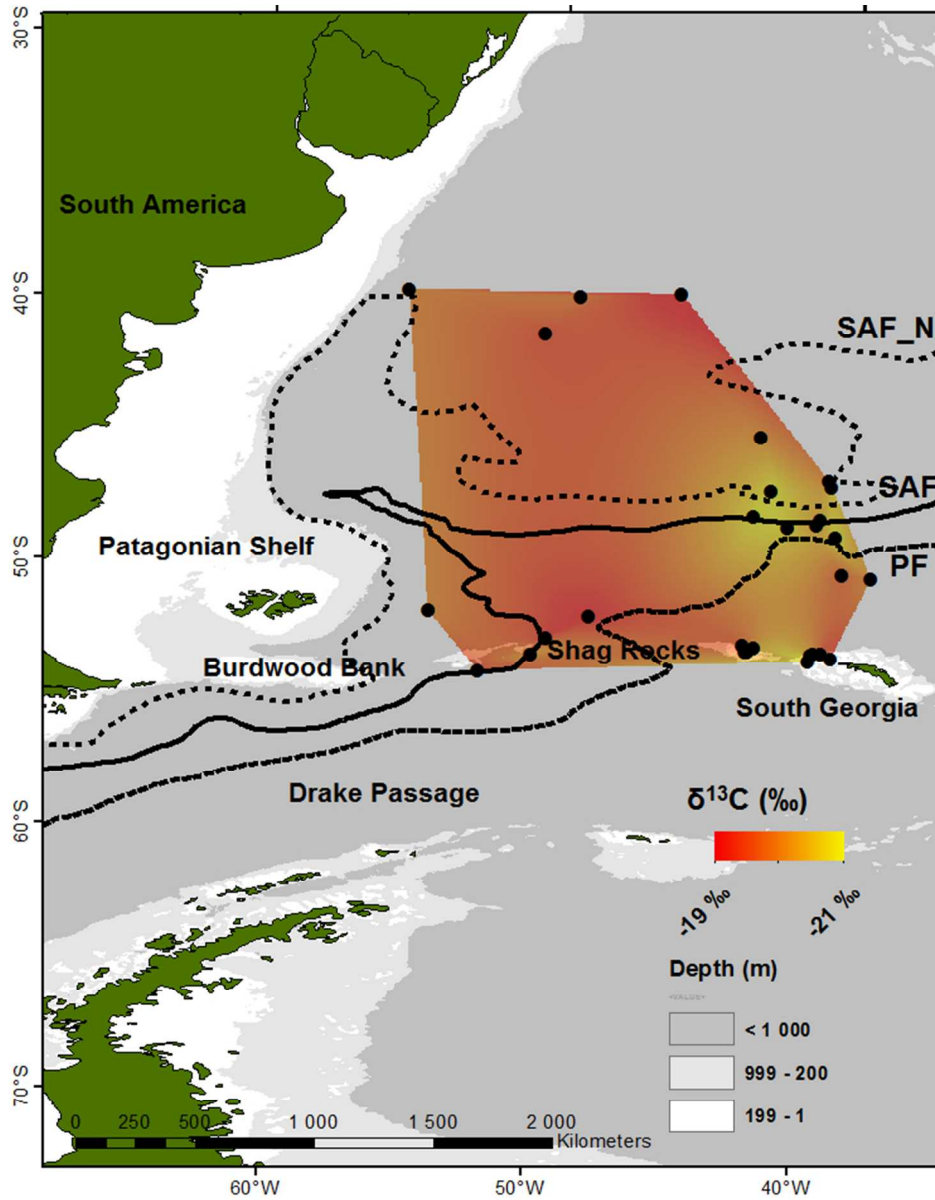
529 **FIGURE LEGENDS**

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531 **Figure 1.** Estimated isoscape after natural neighbour interpolation from $\delta^{13}\text{C}$ values of
532 delipidated plasma of the 29 wandering albatrosses tracked with both GPS and activity
533 loggers between May and October 2009 from Bird Island, South Georgia. Points
534 represent the mean latitude and longitude of feeding attempts calculated for each bird
535 from immersion data (wet events that lasted >10 mins.). Bathymetry is presented as
536 greyscale (downloaded from <http://www.ngdc.noaa.gov/mgg/global/global.html>,
537 blended ETOPO1 product, grid of 0.01°). The main oceanic fronts as described in
538 Sallée et al.^[17] are indicated as follows: PF - Antarctic Polar Front, SAF - Subantarctic
539 Front and SAF_N - northern extension of the Subantarctic Front.

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