

1 SEABIRDS MAPPING THE OCCURENCE OF ELUSIVE PELAGIC CEPHALOPOD
2 SPECIES

3 JORGE M. PEREIRA¹, VÍTOR H. PAIVA¹, AND JOSÉ C. XAVIER^{1,2}

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5 ¹ *MARE – Marine and Environmental Sciences Centre, Faculdade de Ciências e Tecnologia,*
6 *Universidade de Coimbra, Departamento de Ciências da Vida, 3000-456 Coimbra, Portugal*

7 ² *British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley*
8 *Road, CB3 0ET, Cambridge, UK*

9

10 E-mail: Jormi93@gmail.com

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12 **ABSTRACT**

13 The distribution of oceanic cephalopod species is not fully understood but seabirds, who feed
14 on cephalopods and cover vast oceanic areas, might work as samplers and mappers of the
15 occurrence of this elusive group. We tracked seventeen wandering albatrosses *Diomedea*
16 *exulans* in Bird Island, South Georgia (54°S; 38°W) over the austral winter (breeding period)
17 with GPS-loggers, activity recorders and stomach temperature probes. At logger retrieval, diet
18 composition was accessed via stomach flushings of the tagged individuals. Wandering
19 albatrosses captured circumpolar and rarer oceanic squid in all water masses of the Southern
20 Ocean (i.e. Antarctic, sub-Antarctic and subtropical waters), complementing much of the
21 knowledge about the cephalopod distribution in the Atlantic sector of the Southern Ocean.
22 Some cephalopod species showed a wider distribution range, suggesting that despite of the
23 oceanic fronts represent ecological barriers that limit their distribution, they are capable of
24 overcoming these frontal regimes and even taking advantage of their waters as migration
25 pathways.

26

27 **KEYWORDS:** Southern Ocean, Stomach Temperature Probes, Wandering albatrosses,
28 Cephalopods, Prey distribution

29

30 INTRODUCTION

31

32 Distribution data of most marine groups is absent in remote marine areas, such as the
33 vast Southern Ocean (considered in this study, as south of the subtropical front; (Xavier et al.
34 2014). Information on fast swimming oceanic prey, such as squid, is particularly difficult as
35 they appear rarely in scientific nets (Xavier et al. 2006). Many marine predators as fish
36 (Patagonian toothfish *Dissostichus eleginoides*) or seabirds (albatrosses) were commonly used
37 for study cephalopods occurrence/distribution in Southern Ocean once they are eaten by higher
38 predators, providing unique information about their ecology (Cherel & Weimerskirch 1995,
39 Pilling 2001, Xavier et al. 2002). Previous study has used wandering albatrosses *Diomedea*
40 *exulans* as biological samplers to provide information about biogeography of oceanic prey,
41 through probabilistic models based on satellite tracking and activity loggers data (Xavier et al.
42 2006) and habitat suitability modelling (Xavier et al. 2016).

43 Wandering albatrosses are wide distribution seabirds, known to travel long distances
44 between the areas where they forage, covering huge areas of the Southern Ocean. During the
45 chick-rearing period wandering albatrosses from South Georgia attend long distances over the
46 Southern Ocean, foraging over colder water of Antarctic region but also in warmer waters of
47 the sub-Antarctic and sub-tropical region, in order to provide food to their chicks in the breeding
48 colony (Xavier et al. 2004). Wandering albatrosses are opportunistic and highly generalist,
49 being their diet composed mostly by fish and cephalopods, preyed by surface-feeding in
50 epipelagic waters (Cherel & Klages 1998, Xavier et al. 2004, Xavier & Croxall 2005).

51 Crustaceans, gelatinous bodies (jellyfishes) and carrion are minor components of their diet.
52 Although the fish components in the diet of wandering albatrosses has been well described,
53 information on its cephalopod prey in Southern Ocean remains still unpredictable and unknown.
54 Though recent technological developments, such as GPS tracking (providing higher accuracy
55 on the geographical position of the predator) and stomach temperature probes (providing the
56 size and time of prey ingested), have been advocated as powerful methods to map the
57 distribution of poorly known marine species (Wilson et al. 1992, Wilson et al. 1995, Catry et
58 al. 2004, Ropert-Coudert & Kato 2006).

59 Most of the cephalopod species preyed by wandering albatrosses are distributed at South
60 of the Antarctic Polar Front (APF), suggesting that diet composition of wandering albatrosses
61 are mostly composed by endemic species of Antarctic waters (Xavier et al. 1999, Xavier et al.
62 2003). *Kondakovia longimana*, *Alluroteuthis antarcticus*, *Moroteuthis knipovitchi*, *Galiteuthis*
63 *glacialis* and *Histioteuthis eltaninae* are considered endemic of Antarctic waters whereas
64 *Histioteuthis machrohista* and *Histioteuthis eltaninae* were geographically distributed in sub-
65 Antarctic and sub-tropical waters (Xavier et al. 1999, Rodhouse et al. 2014, Xavier et al. 2016).

66 In our study, we report the occurrence and location of cephalopod species in the Atlantic
67 sector of the Southern Ocean using biologging devices together with dietary data of wandering
68 albatrosses in Bird Island, South Georgia during the chick-rearing period.

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70

71 MATERIAL AND METHODS

72

73 Seventeen wandering albatrosses were tracked from Bird Island, South Georgia (54° S
74 38° W) during the chick-rearing period. Each albatross was fitted with three devices: (1) Global
75 Positioning System (GPS) logger, (2) activity recorder and (3) stomach temperature probe

76 loggers. The GPS logger (100 x 48 x 24 mm, 70 grams; Jensen Software Systems, Kiel,
77 Germany) was programmed to store the geographical position of each individual each 20
78 minutes. Each bird was also fitted with an activity recorder, called MK7 (18 x 18 x 6.5 mm, 3.6
79 grams; British Antarctic Survey) to detect wet and dry events. The activity recorder registered
80 the percentage of time spent by the seabird on the sea surface in a continuous 10-min recording
81 period (Xavier et al. 2006). In addition, wandering albatrosses were also fitted with stomach
82 temperature probe loggers (19 mm diameter x 150 mm long, 51.5 grams; Jensen Software
83 Systems, Kiel, Germany), to record temperature drops, and thus infer feeding events of cold
84 prey items (Wilson et al. 1992, Wilson et al. 1995, Weimerskirch et al. 2007). All devices were
85 recovered and successfully downloaded after a single journey.

86 The combined analysis of the tracking and activity recorder data allowed us to identify
87 flight and in water periods. A frequency distribution histogram was used to explore the stomach
88 temperature data and set a threshold cut-off to distinguish prey capture events ($STP < 37^{\circ} C$)
89 from water ingestion ($STP \geq 37^{\circ} C$) (Figure 1).

90 Diet samples were collected from each bird and only fresh items were used to make sure
91 identified prey items corresponded only to the tracked foraging trip (Xavier et al. 2003).
92 Stomach contents were then sorted at the lab and fish, cephalopod and crustacean components
93 identified, through fish otoliths, cephalopod beaks and whole crustaceans (or parts of; e.g.
94 carapaces), respectively, with the help of different identification guides (Xavier et al. 2004,
95 Xavier & Cherel 2009). No stomach contents were taken from chicks. Only fresh prey items
96 were quantified to avoid overestimation on the overall wandering albatross diet composition.
97 Reconstructed mass (M in grams) and length (L in millimetres) of prey were estimated using
98 allometric equations and further related with the mass calculated for the ingestion points.

99 Mass of prey was estimated for the location of ingestion with the help of the MT-Dive
100 software, module MT-Temp (Jensen Software Systems, Kiel, Germany). After an ingestion

101 event (food or water), occurs a precipitous temperature drop followed by an approximately
 102 exponential rise event (PDER) (Wilson et al. 1992, Wilson et al. 1995). In order to quantify
 103 wandering albatross ingestion mass in each PDER event we used the methodologies described
 104 by Wilson et al. (1995). Thus, it was possible to calculate the mass of the food (M) associated
 105 with each PDER event by rearranging the equations following Wilson et al. (1995) (see
 106 equation 1):

107

$$108 \quad M = \text{INT} / [m \times \text{SHC} \times (T_a - T_f)] \quad \text{Equation 1}$$

109

110 Where INT represents the integral of the PDER drop from the moment the food is
 111 ingested until the temperature reaches the asymptote, m describes the gradient of the slope, SHC
 112 which is the specific heat of the substance ingested item (joules per gram per degree Celsius),
 113 T_f the temperature and T_a the temperature to which the food must be heated (in degree Celsius).
 114 Prey items ingested were at 5.5° C (mean local water temperature; water SHC) and their SHC
 115 was assumed to be 4.0 J g⁻¹ °C⁻¹ (Wilson et al. 1995, Pütz et al. 1998, Catry et al. 2004).

116 In order to distinguish prey ingestion from ‘drinking water’ events (i.e. feeding
 117 attempts), we applied an *I*-Index described by Catry et al. (2004) (see equation 2):

118

$$119 \quad I = t_{0.5} (T_{\text{init}} - T_{\text{min}}) \quad \text{Equation 2}$$

120

121 Where T_{init} is the temperature at the onset of an ingestion event, T_{min} is the lowest
 122 temperature achieved during the ingestion event and $T_{0.5}$ is the time it takes from the start of
 123 the ingestion (in seconds) to the point where the temperature ascended from T_{min} to a value that
 124 corresponds to the mean of T_{init} and T_{min} (Catry et al. 2004).

125 Of the seventeen tracked wandering albatrosses a total of 192 ingestion events, were
126 excluded from the analysis the ingestion of water or gelatinous bodies (18% of ingestion
127 events). Of the ingestion events that were assumed to be solid ingestions, all the 22 fresh squid
128 specimens found in wandering albatrosses stomach contents were associated with prey capture
129 events (similar estimated masses). Prey capture events were analyzed in the GIS environment
130 and plotted using ArcMap mode of ESRI software, ArcGIS version 10.3. Since similar prey
131 mass ingestions could add some uncertainty in prey distribution and in order to increase the
132 accuracy of where the items were preyed, it was decided to connect the PDER with meals of
133 similar mass.

134 **RESULTS AND DISCUSSION**

135

136 Seabirds are considered one of the best biological samplers by excellence to assess the
137 distribution of organisms in marine and patchy environments. Once is almost impossible to
138 observe individual animals over wide areas and extended periods, the attachment of biological
139 devices in wide distribution predators seemed to be the best strategy to study the interaction
140 between marine predators and marine patchy environments (Hooker et al. 2007). Biologging
141 provided to study many aspects of behaviour and ecology of marine predators (e.g. foraging
142 behaviour, preying strategies, attendance patterns and distribution) but also their prey (Wilson
143 et al. 1992). The incorporation of physiological sensors and diet information to movement data
144 allow to study the behaviour ecology of marine predators, namely feeding-knowing where and
145 when animals feed at a fine scale (Wilson et al. 1995, Catry et al. 2004, Phillips et al. 2007).
146 We mapped the probable distribution of oceanic squid within the Atlantic region of the Southern
147 Ocean. Our study showed that GPS tracking of wandering albatrosses with activity recorders
148 and stomach temperature probes combined with diet composition from stomach contents,
149 allowed to infer the distribution of oceanic squid species in the Southern Ocean. Cephalopods

150 play an important role in Southern Ocean ecosystem, as predators but also as prey. Wandering
151 albatrosses are cephalopod predators, which specialize in feeding on a wide range of oceanic
152 squid and octopod species in subtropical waters in the north to Antarctic waters in the south
153 (Xavier & Croxall 2005). During the chick-rearing period, wandering albatrosses adults may
154 provide almost 60 different cephalopod species to their chicks (Xavier et al. 2014). According
155 to our analysis, oceanic squid were caught by wandering albatrosses in all water masses (i.e.
156 Antarctic, sub-Antarctic and subtropical waters) (Figure 2). A total of 11 squid species (n=22
157 individuals) were found in the diet of wandering albatrosses (Table I), complementing much of
158 the known distribution of squid in the region. For instance, our study showed that *Galiteuthis*
159 *glacialis* (n=8) can also be distributed in warmer and oceanic sub-Antarctic waters of the
160 Argentine abyssal plain, as well as in Antarctic waters, bounded North by the Sub-Antarctic
161 Front (SAF) (Xavier et al. 2016). These results indicate a wider distribution range of *G. glacialis*
162 towards northern latitudes, once oceanic fronts doesn't seem to limit their occurrence, according
163 to the existing distribution knowledge (Rodhouse et al. 1987, Xavier et al. 1999, Xavier et al.
164 2006, Xavier et al. 2016). (Figure 2). Various species (e.g. *Alluroteuthis antarcticus*,
165 *Moroteuthis knipovitchi*) caught in the Atlantic sector of the Southern Ocean confirmed their
166 circumpolar distribution (Xavier et al. 1999). For rarer species, their distribution also agreed
167 with previous studies performed in different water masses. For instance, *H. eltaninae* (n=1) was
168 caught in Antarctic waters, whereas *Histioteuthis miranda* (n=1) in sub-Tropical waters,
169 agreeing with known distribution of smaller individuals of these species caught by nets (Xavier
170 et al. 1999). Almost all the squid species caught by wandering albatrosses were likely to have
171 been taken alive once their estimated mass rarely overcome 500 g. Squid species such as
172 *Taningia danae* with an estimated mass of 2764 g are too big to have been ingested intact by a
173 wandering albatross and was likely to be scavenged. Despite of the small size, was decided to
174 not map the *Illex argentinus* occurrence, once it is a usual species used in fisheries, becoming

175 available for wandering albatrosses by fishing bait. *Illex argentinus* were caught by wandering
176 albatrosses near South Georgia shelf slope, suggesting that have been transported from
177 Patagonian shelf, where is usually used as fisheries bait to their feeding ground in Antarctic
178 waters though the APF from the SAF (Sub Antarctic Front) gyres or core rings (Xavier et al.
179 2006, Seco et al. 2016). Also as the large squid species, such as *kondakovia longimana* or
180 *Taningia danae*, wandering albatrosses consumed large fish species. Demersal species as
181 *Dissostichus eleginoides* and *Antimora rostrata* are unavailable to wandering albatrosses take
182 them alive because both are bottom-dwelling fish and can reach large sizes and mass (Xavier
183 et al. 2004). Despite of the fact that how these prey species become available to wandering
184 albatrosses is still unclear, but is likely that *Dissostichus eleginoides* and *Antimora rostrata*,
185 demersal fishes that does not occur near the surface, could become available as offal/ discards
186 from longline fisheries (Xavier et al. 2003, Jiménez et al. 2014, Jiménez et al. 2016).

187 Overall, our results showed that GPS tracking of marine predators with activity
188 recorders and stomach temperature probes combined with diet composition from stomach
189 contents proved to be a valid method to infer the occurrence of oceanic squid species in patchy
190 and oceanic environments, such as Southern Ocean (Ropert-Coudert & Kato 2006). Future
191 studies should 1) increase the number of seabird and other top predator species being tracked
192 in order to cover unknown parts of the ocean and 2) use small cameras in those deployments,
193 in order to understand and validate the identified prey distribution patterns but also reduce the
194 uncertainty inherent to this methodology relate with food discarded by fishing vessels (Hooker
195 et al. 2002, Takahashi et al. 2004, Votier et al. 2013).

196

197 **ACKNOWLEDGEMENTS**

198

199 We thank Richard Phillips and Derren Fox and the team of research assistants of the
 200 British Antarctic Survey. JCX is supported by the Investigator 'Fundação para a Ciência e
 201 Tecnologia' (FCT) program (IF/00616/2013) and VHP by an FCT fellowship
 202 (SFRH/BPD/85024/2012). This work is part of SCAR AnT-ERA, ICED, PROPOLAR, BAS-
 203 CEPH programs and had the support of, the strategic project UID/MAR/04292/2013 granted to
 204 MARE.

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283 **Table I.** Composition of diet samples obtained from 17 wandering albatrosses at Bird Island,
 284 South Georgia during the austral winter 2009. Only fresh prey items were quantified to avoid
 285 overestimation on the overall wandering albatross diet composition.

Taxon	Individual prey (n)	Estimated prey mass (g) (mean \pm SD)	Estimated prey length (mm) (mean \pm SD)
Squid	22	542 \pm 775	235 \pm 138
Family Cranchiidae			
<i>Galiteuthis glacialis</i>	8	104 \pm 4.5	456 \pm 8.8
<i>Taonius</i> sp. B (Voss)	2	451 \pm 168	367 \pm 185
Family Gonatidae			
<i>Gonatus antarcticus</i>	1	507	295
Family Histioteuthidae			
<i>Histioteuthis atlantica</i>	1	109	85
<i>Histioteuthis eltaninae</i>	1	75	84
<i>Histioteuthis macrohista</i>	1	96	53
<i>Histioteuthis miranda</i>		839	210
Family Neotheulidae			
<i>Alluroteuthis antarcticus</i>	1	517	188
Family Octopoteuthidae			
<i>Taningia danae</i>	1	2764	428
Family Ommastrephidae			
<i>Illex argentinus</i>	2	191 \pm 63	224 \pm 10
Family Onychoteuthidae			
<i>Moroteuthis knipovitchi</i>	3	312 \pm 180	196 \pm 232
Fish	6	2053 \pm 2684	475 \pm 232
Family Macrouridae			
	1	45	220
Family Moridae			
<i>Antimora rostrata</i>	2	1012 \pm 247	529 \pm 37

Family Nototheniidae

Dissostichus eleginoides

3

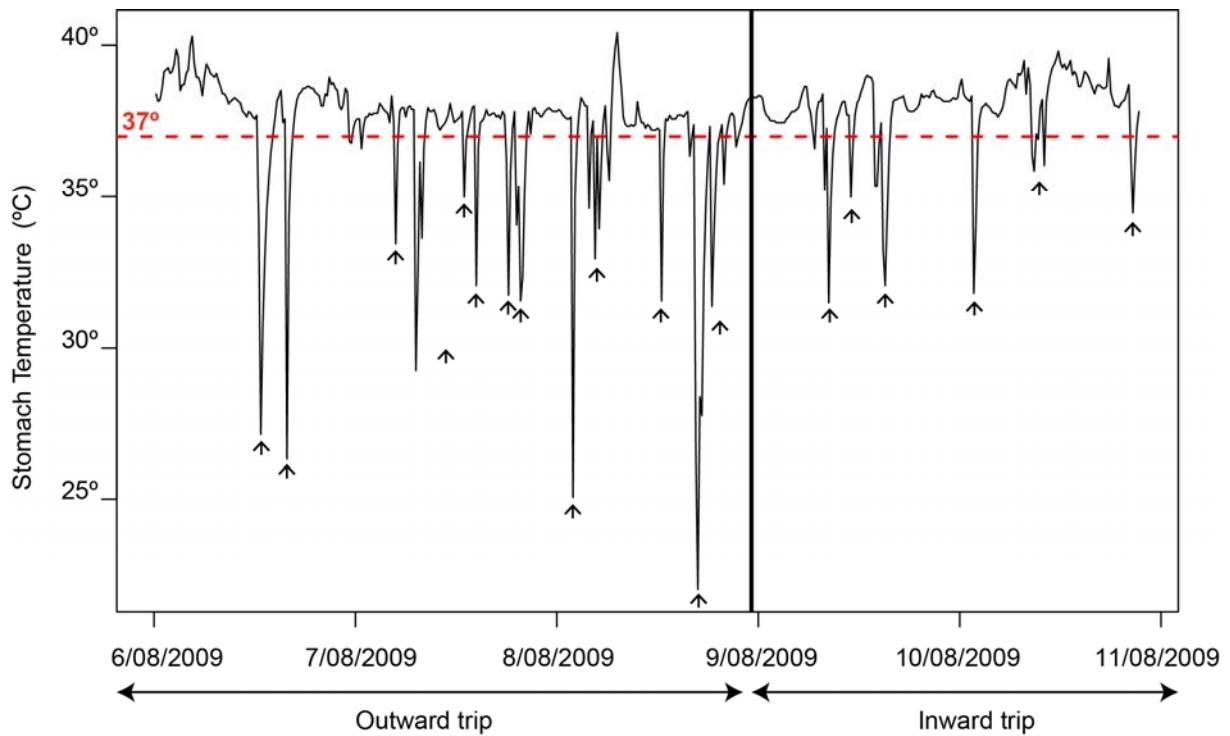
5102 ± 2327

675 ± 93

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289

290 **Figure 1.** Stomach temperature from a foraging trip recorded in a wandering albatross female by a stomach temperature
 291 probe. Dashed red line marks the threshold cut-off used to identify PDER events. Ingestion events are shown as vertical arrows.
 292 Bold line marks the inflection point in the foraging trip, where wandering albatross change their flight direction and return to
 293 the breeding colony.

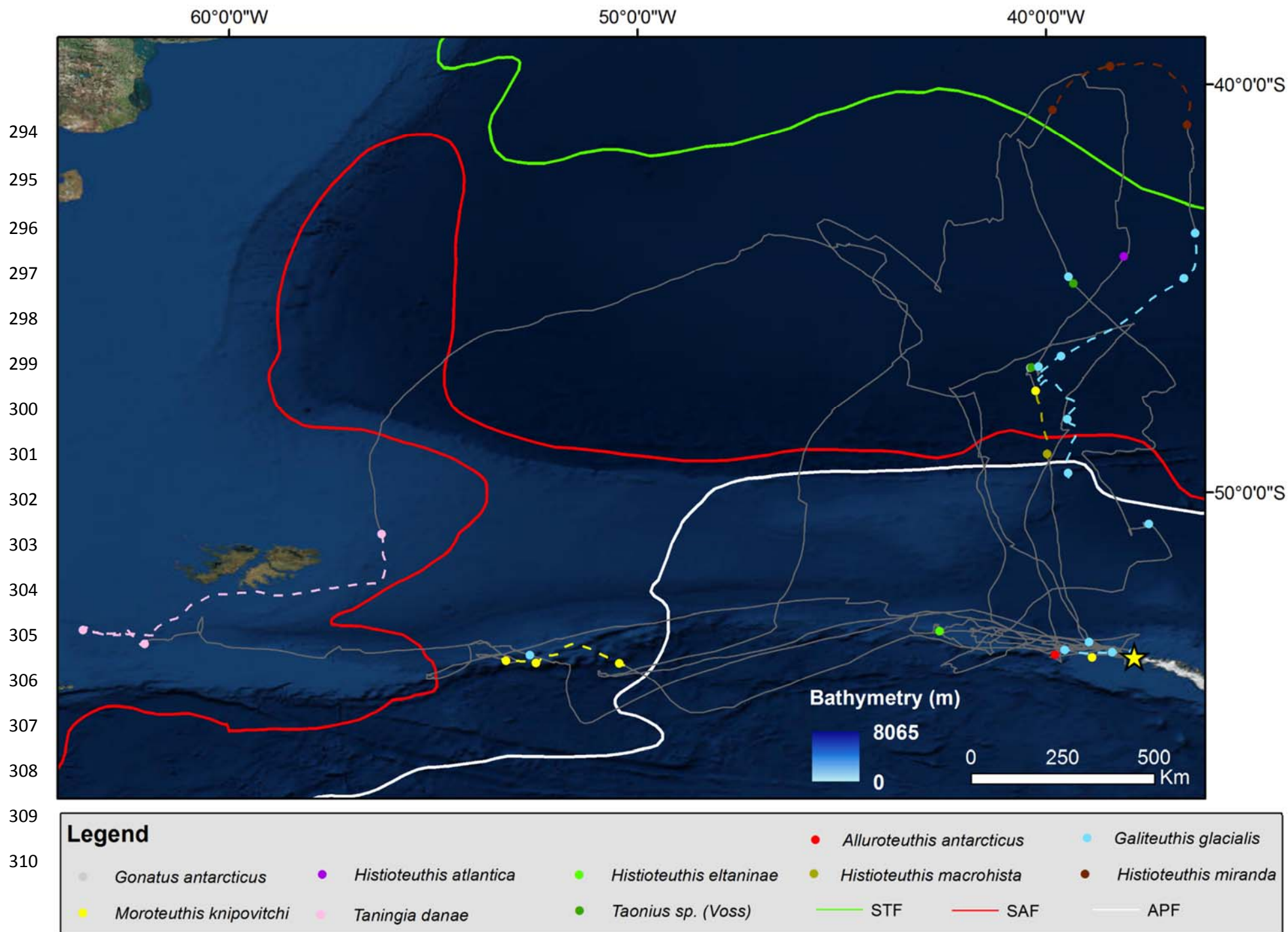


Figure 2. Locations of cephalopod species (coloured dots) captured by Wandering albatrosses from Bird Island, South Georgia (yellow star). Dashed lines depict cases of uncertainty between pairs of locations, because of similar estimated mass of both cephalopods. The position of the Sub-Tropical Front (STF), Sub-Antarctic Front (SAF) and Antarctic Polar Front (APF) are also shown in the map overlaid on the bathymetry of the region.



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