SEABIRDS MAPPING THE OCCURENCE OF ELUSIVE PELAGIC CEPHALOPOD SPECIES

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ABSTRACT

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

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

INTRODUCTION

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

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

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

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

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

MATERIAL AND METHODS

Seventeen wandering albatrosses were tracked from Bird Island, South Georgia (54° S 38° W) during the chick-rearing period. Each albatross was fitted with three devices: (1) Global Positioning System (GPS) logger, (2) activity recorder and (3) stomach temperature probe loggers. The GPS logger (100 x 48 x 24 mm, 70 grams; Jensen Software Systems, Kiel, Germany) was programmed to store the geographical position of each individual each 20 minutes. Each bird was also fitted with an activity recorder, called MK7 (18 x 18 x 6.5 mm, 3.6 grams; British Antarctic Survey) to detect wet and dry events. The activity recorder registered the percentage of time spent by the seabird on the sea surface in a continuous 10-min recording period (Xavier et al. 2006). In addition, wandering albatrosses were also fitted with stomach temperature probe loggers (19 mm diameter x 150 mm long, 51.5 grams; Jensen Software Systems, Kiel, Germany), to record temperature drops, and thus infer feeding events of cold prey items (Wilson et al. 1992, Wilson et al. 1995, Weimerskirch et al. 2007). All devices were recovered and successfully downloaded after a single journey.

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

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

Mass of prey was estimated for the location of ingestion with the help of the MT-Dive software, module MT-Temp (Jensen Software Systems, Kiel, Germany). After an ingestion event (food or water), occurs a precipitous temperature drop followed by an approximately exponential rise event (PDER) (Wilson et al. 1992, Wilson et al. 1995). In order to quantify wandering albatross ingestion mass in each PDER event we used the methodologies described by Wilson et al. (1995). Thus, it was possible to calculate the mass of the food (M) associated with each PDER event by rearranging the equations following Wilson et al. (1995) (see equation 1):

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

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

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

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

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

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

RESULTS AND DISCUSSION

Seabirds are considered one of the best biological samplers by excellence to assess the distribution of organisms in marine and patchy environments. Once is almost impossible to observe individual animals over wide areas and extended periods, the attachment of biological devices in wide distribution predators seemed to be the best strategy to study the interaction between marine predators and marine patchy environments (Hooker et al. 2007). Biologging provided to study many aspects of behaviour and ecology of marine predators (e.g. foraging behaviour, preying strategies, attendance patterns and distribution) but also their prey (Wilson et al. 1992). The incorporation of physiological sensors and diet information to movement data allow to study the behaviour ecology of marine predators, namely feeding-knowing where and when animals feed at a fine scale (Wilson et al. 1995, Catry et al. 2004, Phillips et al. 2007). We mapped the probable distribution of oceanic squid within the Atlantic region of the Southern Ocean. Our study showed that GPS tracking of wandering albatrosses with activity recorders and stomach temperature probes combined with diet composition from stomach contents, allowed to infer the distribution of oceanic squid species in the Southern Ocean. Cephalopods play an important role in Southern Ocean ecosystem, as predators but also as prey. Wandering albatrosses are cephalopod predators, which specialize in feeding on a wide range of oceanic squid and octopod species in subtropical waters in the north to Antarctic waters in the south (Xavier & Croxall 2005). During the chick-rearing period, wandering albatrosses adults may provide almost 60 different cephalopod species to their chicks (Xavier et al. 2014). According to our analysis, oceanic squid were caught by wandering albatrosses in all water masses (i.e. Antarctic, sub-Antarctic and subtropical waters) (Figure 2). A total of 11 squid species (n=22 individuals) were found in the diet of wandering albatrosses (Table I), complementing much of the known distribution of squid in the region. For instance, our study showed that *Galiteuthis glacialis* (n=8) can also be distributed in warmer and oceanic sub-Antarctic waters of the Argentine abyssal plain, as well as in Antarctic waters, bounded North by the Sub-Antarctic Front (SAF) (Xavier et al. 2016). These results indicate a wider distribution range of *G. glacialis* towards northern latitudes, once oceanic fronts doesn't seem to limit their occurence, according to the existing distribution knowledge (Rodhouse et al. 1987, Xavier et al. 1999, Xavier et al. 2006, Xavier et al. 2016). (Figure 2). Various species (e.g. *Alluroteuthis antarcticus*, *Moroteuthis knipovitchi*) caught in the Atlantic sector of the Southern Ocean confirmed their circumpolar distribution (Xavier et al. 1999). For rarer species, their distribution also agreed with previous studies performed in different water masses. For instance, *H. eltaninae* (n=1) was caught in Antarctic waters, whereas *Histioteuthis miranda* (n=1) in sub-Tropical waters, agreeing with known distribution of smaller individuals of these species caught by nets (Xavier et al. 1999). Almost all the squid species caught by wandering albatrosses were likely to have been taken alive once their estimated mass rarely overcome 500 g. Squid species such as *Taningia danae* with an estimated mass of 2764 g are too big to have been ingested intact by a wandering albatross and was likely to be scavenged. Despite of the small size, was decided to not map the *Illex argentinus* occurence, once it is a usual species used in fisheries, becoming available for wandering albatrosses by fishing bait. *Illex argentinus* were caught by wandering albatrosses near South Georgia shelf slope, suggesting that have been transported from Patagonian shelf, where is usually used as fisheries bait to their feeding ground in Antarctic waters though the APF from the SAF (Sub Antarctic Front) gyres or core rings (Xavier et al. 2006, Seco et al. 2016). Also as the large squid species, such as *kondakovia longimana* or *Taningia danae*, wandering albatrosses consumed large fish species. Demersal species as *Dissostichus eleginoides* and *Antimora rostrata* are unavailable to wandering albatrosses take them alive because both are bottom-dwelling fish and can reach large sizes and mass (Xavier et al. 2004). Despite of the fact that how these prey species become available to wandering albatrosses is still unclear, but is likely that *Dissostichus eleginoides* and *Antimora rostrata*, demersal fishes that does not occur near the surface, could become available as offal/ discards from longline fisheries (Xavier et al. 2003, Jiménez et al. 2014, Jiménez et al. 2016).

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

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

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

Family Nototheniidae			
Dissostichus eleginoides	3	5102 ± 2327	675 ± 93

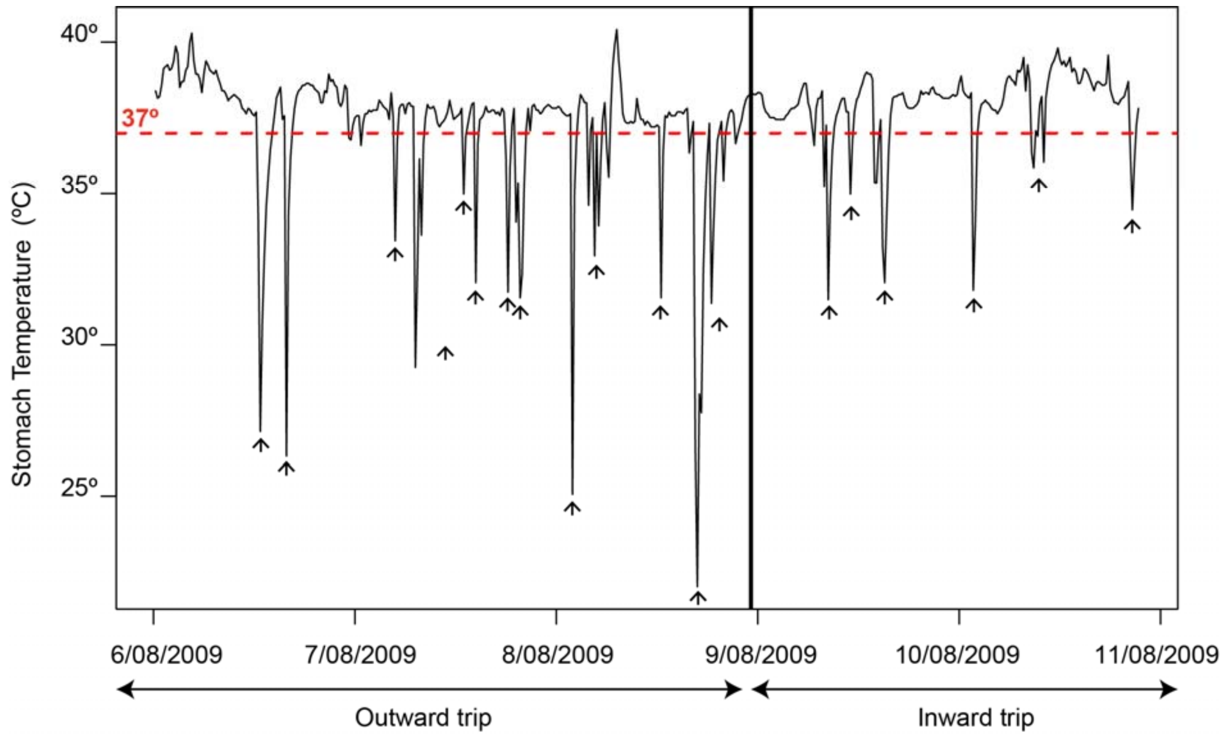

Figure 1. *Stomach temperature from a foraging trip recorded in a wandering albatross female by a stomach temperature probe. Dashed red line marks the threshold cut-off used to identify PDER events. Ingestion events are shown as vertical arrows. Bold line marks the inflection point in the foraging trip,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

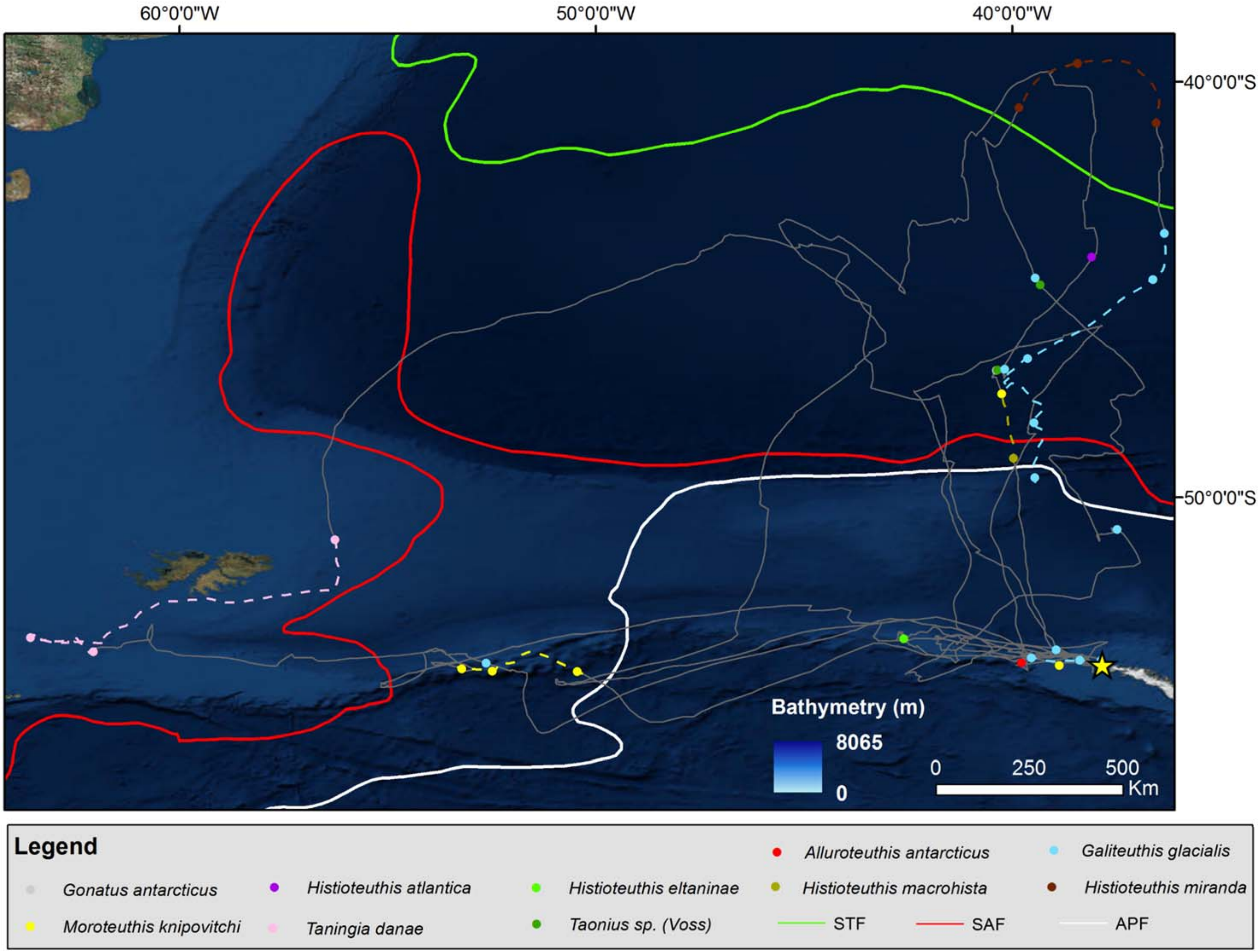

Figure 2. *Locations of cephalopod species (coloured dots) captured by Wandering albatrosses from Bird Island, South Georgia (yellow star). Dashed lines depict cases of uncertainty between pairs of locations, because of similar estimated mass of both cephalopods. The position of the Sub-Tropical Front (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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