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NOTE

Using seabirds to map the distribution of elusive pelagic cephalopod species

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ABSTRACT: The distribution of oceanic cephalopod species is not fully understood but seabirds, which feed on cephalopods and cover vast oceanic areas, might work as samplers and mappers of the occurrence of this elusive group. We tracked 17 wandering albatrosses *Diomedea exulans* at 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 distribution range wider than expected, with oceanic fronts not functioning as ecological barriers as previously thought. This suggests they might be capable of overcoming these frontal regimes and even take advantage of their dynamics as migration pathways.

KEY WORDS: 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 as south of the subtropical front in this study; 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, such as fish (Patagonian toothfish *Dissostichus eleginoides*) or seabirds (albatrosses), that feed on cephalopods have commonly been used to study their occurrence or distribution in the Southern Ocean, providing unique information about their ecology (Cherel & Weimerskirch 1995, Pilling 2001, Xavier et al. 2002). Xavier et al. (2006) used wandering albatrosses *Diomedea exulans* as biological samplers to provide information about the biogeography of oceanic prey, through probabilistic models based on satellite tracking and data from activity loggers.

Wandering albatrosses have a wide at-sea distribution, foraging over vast oceanic expanses. During the chick-rearing period, wandering albatrosses from South Georgia travel long distances over the Southern Ocean, foraging over the colder water of the Antarctic region but also in the warmer waters of the sub-Antarctic and subtropical regions (Xavier et al. 2004). Wandering albatrosses are opportunistic and highly generalist, feeding mostly on fish and cephalopods (squid can reach >40% by mass of the diet), caught by surface-seizing in epipelagic waters (Cherel & Klages 1998, Xavier et al. 2004, Xavier & Croxall 2005). Although the fish component of their diet has been well described, information on their

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cephalopod prey in the Southern Ocean remains scarce. However, recent technological developments, such as GPS tracking (providing more accurate geographical positioning of the predator) and stomach temperature probes (providing the size of prey and time ingested), have been advocated as powerful methods to map the distribution of poorly known marine species (Wilson et al. 1992, 1995, Catry et al. 2004, Ropert-Coudert & Kato 2006).

Cephalopod species preyed upon by wandering albatrosses are thought to be mostly distributed in Antarctic, sub-Antarctic and subtropical waters (Xavier et al. 1999, 2003). For instance, *Kondakovia longimana*, *Alluroteuthis antarcticus*, *Moroteuthis knipovitchi* and *Galiteuthis glacialis* are distributed in Antarctic waters, whereas *Histioteuthis macrohista* and *H. eltaninae* are geographically distributed in more sub-Antarctic and subtropical waters (Xavier et al. 1999, 2016, Rodhouse et al. 2014).

In this study, we intend to provide further insight into the distribution of elusive cephalopod species inhabiting the Atlantic sector of the Southern Ocean. To attain this, we used the wandering albatross population of Bird Island (South Georgia) as biological samplers, by tracking their movements with biologging devices and accessing their diet after each foraging excursion.

MATERIALS AND METHODS

A total of 17 wandering albatrosses were tracked from Bird Island, South Georgia (54° S, 38° W) during the chick-rearing period. Each albatross was fitted with 3 devices: (1) global positioning system (GPS) logger, (2) activity recorder and (3) stomach temperature probe logger. The GPS logger (100 × 48 × 24 mm, 70 g; Jensen Software Systems) was programmed to store the geographical position of each individual every 20 min. Each bird was also fitted with an MK7 activity recorder (18 × 18 × 6.5 mm, 3.6 g; 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. In addition, wandering albatrosses were also fitted with stomach temperature probe loggers (19 mm diameter × 150 mm long, 51.5 g; Jensen Software Systems) to record temperature drops, and thus infer feeding events of cold prey items (Wilson et al. 1992, 1995, Ropert-Coudert & Kato 2006, 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 (ST) data and set a threshold cut-off to distinguish prey capture events ($ST < 37°C$) from water ingestion ($ST \geq 37°C$) (Fig. 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 laboratory, and fish, cephalopod and crustacean components were identified through fish otoliths, cephalopod beaks and whole crustaceans (or parts 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 of the overall wandering albatross diet composition. Reconstructed mass (M in g) and length (L in mm) of prey were estimated using allometric equations and further related to 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). After an ingestion event (food or water), a precipitous temperature drop followed by an approximately exponential rise event (PDER) occurs (Weimerskirch & Wilson 1992, Wilson et al. 1992, Ropert-Coudert & Kato 2006). 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 using the following equation (Wilson et al. 1995):

$$M = \mathrm{INT} / [m \times \mathrm{SHC} \times (T_a - T_f)] \tag{1}$$

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 is the specific heat capacity of the substance ingested (J g^{-1} $°C^{-1}$), T_f the temperature and T_a the temperature to which the food must be heated (°C). Ingested prey items 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 as described by Catry et al. (2004):

$$I = T_{0.5}\,(T_{\mathrm{init}} - T_{\mathrm{min}}) \tag{2}$$

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 (s) 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).

For the 17 tracked wandering albatrosses, a total of 192 ingestion events were recorded after the ingestion of water or gelatinous bodies (18% of ingestion events) had been excluded from the analysis. Of the ingestion events that were assumed to be solid ingestions, all of the 22 fresh squid specimens found in wandering albatrosses stomach contents could be associated with prey capture events (similar estimated masses). Prey capture events were analysed in the GIS environment and plotted using the ArcMap mode of the ESRI software, ArcGIS version 10.2. Since similar prey mass ingestions could add some uncertainty to the prey distribution and in order to increase the accuracy of where the items were caught, we decided to connect the PDER events with meals of similar mass.

RESULTS AND DISCUSSION

Seabirds are considered one of the best biological samplers to assess the distribution of organisms in marine and patchy environments. Although it is almost impossible to observe individual animals over wide areas and extended periods, the attachment of biological devices to wide distribution predators appears to be the best strategy to study the interaction between marine predators and marine patchy environments (Hooker et al. 2007). Biologging enables the study of many aspects of the behaviour and ecology of marine predators (e.g. foraging behaviour, preying strategies, attendance patterns and distribution) and also their prey (Weimerskirch & Wilson 1992, Wilson et al. 1992). The combination of physiological sensors and diet information with movement data allows the study of the behavioural ecology of marine predators, namely determining where and when animals feed on a fine-scale (Wilson et al. 1995, Catry et al. 2004, Phillips et al. 2007).

We mapped the probable occurrence 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 us to infer the distribution of oceanic squid species in the Southern Ocean. According to our analysis, oceanic squid were caught by wandering albatrosses in all water masses (i.e. Antarctic, sub-Antarctic and subtropical waters) (Fig. 2). A total of 11 squid species (n = 22 individuals) were found in the diet of wandering albatrosses (Table 1), 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 to the north by the Sub-Antarctic Front (SAF) (Xavier et al. 2016). These results indicate a

Table 1. Composition of diet samples obtained from 17 wandering albatrosses *Diomedea exulans* at Bird Island, South Georgia during austral winter 2009. Only fresh prey items were quantified to avoid overestimation of 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	1	839	210
Family Alluroteuthidae			
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

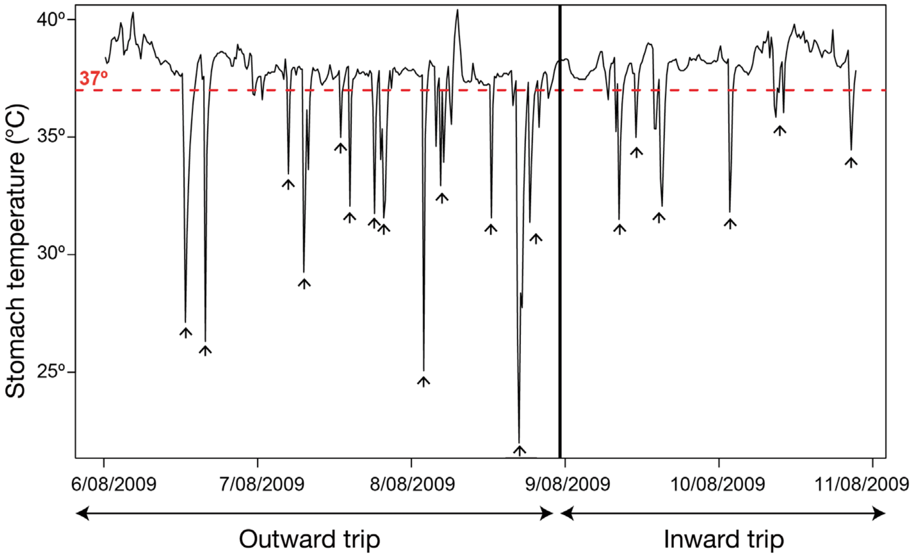

Fig. 1. Stomach temperature from a foraging trip recorded in a female wandering albatross *Diomedea exulans* by a stomach temperature probe. Dashed red line indicates the threshold cut-off used to identify PDER (precipitous temperature drop followed by an approximately exponential rise) events; vertical arrows are ingestion events. The vertical bold line marks the inflection point in the foraging trip where the wandering albatross changed flight direction and returned to the breeding colony. Dates given as d/mo/yr

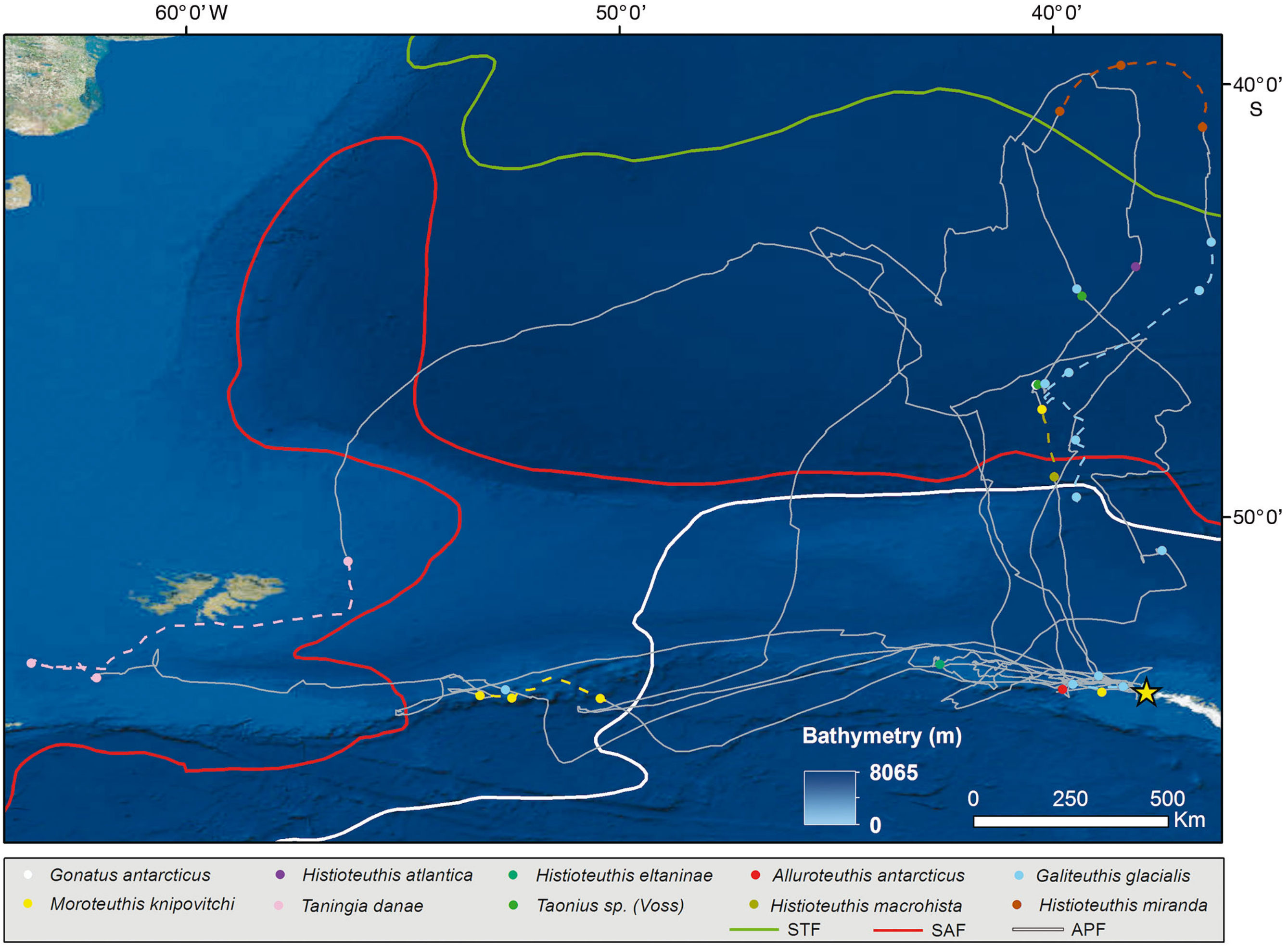

Fig. 2. Locations of cephalopod species (coloured dots) captured by wandering albatrosses *Diomedea exulans* from Bird Island, South Georgia (yellow star). Dashed lines depict cases of uncertainty between pairs of locations, due to similar estimated mass of both cephalopods. The position of the Subtropical Front (STF), Sub-Antarctic Front (SAF) and Antarctic Polar Front (APF) are also shown, overlaid on the bathymetry of the region

wider distribution range of *G. glacialis* towards northern latitudes, and that oceanic fronts do not seem to limit their occurrence (Rodhouse et al. 1987, Xavier et al. 1999, 2006, 2016) (Fig. 2). The capture of various species (e.g. *Alluroteuthis antarcticus*, *Moroteuthis knipovitchi*) in the Atlantic sector of the Southern Ocean confirmed their circumpolar distribution (Xavier et al. 1999, 2016). For rarer species, their distribution also agreed with previous studies performed in different water masses. For instance, *Histioteuthis eltaninae* (n = 1) was caught in Antarctic waters, whereas *H. miranda* (n = 1) was caught in subtropical waters, agreeing with the known distribution of smaller individuals of these species caught by nets (Xavier et al. 1999). Squid species over 500 g have been assumed to be scavenged by wandering albatrosses (Xavier et al. 2003). Squid species such as *Taningia danae*, with an estimated mass of 2764 g (Table 1), are too big to have been ingested intact by a wandering albatross and are likely to have been scavenged. The occurrence of *Illex argentinus* was not illustrated in Fig. 2 as it is known to be used as bait by fishing vessels in the region (Xavier et al. 2006, Seco et al. 2016).

Wandering albatrosses also consumed large fish species. Demersal species such as *Dissostichus eleginoides* and *Antimora rostrata* are likely to be available to wandering albatrosses as offal or discards from longline fisheries operating in the area (Xavier et al. 2003, Jiménez et al. 2014, 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 is a valid method to infer the occurrence of oceanic squid species in patchy and oceanic environments, such as the Southern Ocean. 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 not only understand and validate the identified prey distribution patterns, but also reduce the uncertainty inherent in this methodology in relation to food discarded by fishing vessels (Hooker et al. 2002, Takahashi et al. 2004, Votier et al. 2013).

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