At-sea distribution and diet of an endangered top predator: relationship between white-chinned petrels and commercial longline fisheries

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ABSTRACT: Incidental seabird mortality associated with longline commercial fishing is a worldwide conservation concern. To develop conservation strategies, it is essential to estimate the likelihood of seabird bycatch and the degree of overlap between birds' foraging grounds and commercial fishing areas. We tracked 21 adult white-chinned petrels *Procellaria aequinoctialis* breeding on Kerguelen Island, southern Indian Ocean, during their breeding period in 2006 and in 2008. At-sea foraging distribution of white-chinned petrels was mainly confined to Antarctic waters. Commercial longline fisheries targeting toothfish were operating in both the French Exclusive Economic Zone and in other Commission for the Conservation of Antarctic Marine Living Resources areas during the study. We analysed concurrent data on the positions of both birds and vessels to estimate overlap. Static analysis using indices (home-range and utilization distribution overlap) revealed that, at a large scale, spatial and temporal overlap occurred, but varied among areas and with breeding stage. Dynamic analysis (detection of operating vessels respective to bird locations within a time/space window) revealed little overlap at a small scale. Our study revealed a mismatch between large- and small-scale overlap estimates, suggesting that birds and vessels occupy the same overall zone with infrequent co-occurrence (19% of birds in the vicinity of vessels). This result was confirmed by the relatively low occurrence of fishery-related items (4 to 22%) in chick food samples. However, given the large size of seabird populations, overall, large numbers of birds overlap with vessels, and management authorities should maintain and promote the implementation of strict mitigation measures to further reduce bycatch.

KEY WORDS: Satellite tracking · Toothfish longline fisheries · Petrel · *Procellaria aequinoctialis* · Diet · Spatio-temporal overlap

INTRODUCTION

There is a global marine conservation concern about unsustainably high levels of bycatch in many commercial fisheries (Lewison et al. 2004). Feeding on baited longline hooks is associated with the risk of injury or mortality by being hooked and drowned. Incidental mortality of seabirds on fishing vessels is well docu-

mented, and the level of bycatch is so high (estimated up to 100 000 birds yr^{-1}) that it has resulted in the decline of many species (IUCN 2009, Croxall & Gales 1998). Indeed there is mounting evidence that longline fishing is a major cause of the observed population decreases of many albatrosses and petrels (Weimerskirch et al. 1997, Robertson & Gales 1998, Tuck et al. 2001, Nel et al. 2003, Barbraud et al. 2008, SC-CAMLR

2008). Spatial overlap of seabird distribution with commercial fisheries has therefore been used and endorsed by scientists and management authorities as a tool to assess the extent of potential interactions, and thereby bycatch, and to aid in proposing mitigation measures (Cuthbert et al. 2005, Phillips et al. 2006, Petersen et al. 2008, Trebilco et al. 2008, Copello & Quintana 2009).

During the breeding season, albatrosses and petrels are restricted to waters within commuting distance from their colonies. However, since they can cover long distances from the colonies to their foraging grounds (Catard et al. 2000, Phillips et al. 2006, Pinaud & Weimerskirch 2007) and since fishing operations attract a large range of marine predator species including seabirds (Tasker et al. 2000, Furness 2003), seabirds have the potential of reaching fisheries far away from their breeding grounds. In addition, commercial fisheries and foraging seabirds commonly target the same areas of high productivity. The effect of fisheries on seabird at-sea distribution has also been well documented (Garthe 1997, Weimerskirch 1998, Votier et al. 2004, Bartumeus et al. 2010); fisheries appear to represent additional potential food for opportunistic seabirds in the form of offal, discards and non-target species (González-Zevallos & Yorio 2006, Sullivan et al. 2006). However, the degree to which albatrosses and petrels depend on this food source remains poorly understood, and natural prey might still constitute an important component of their diet (Cherel et al. 2000, 2002).

White-chinned petrels *Procellaria aequinoctialis* are abundant 'ship followers' attracted by vessels (Weimerskirch et al. 2000). They forage by both night and day, and their aggressiveness and ability to dive to depths of several meters make them effective competitors for access to fishing bait, offal and discards (Cherel et al. 1996, Barnes et al. 1997). The association of white-chinned petrels with fishing vessels has been inferred through the incidental mortality monitored in birds and the high levels of incidental bycatch that have been reported at various localities (Weimerskirch et al. 1999, Watkins et al. 2008), including the French Exclusive Economic Zones (EEZ) of Kerguelen and Crozet (Weimerskirch et al. 2000, Delord et al. 2010) in the Southern Ocean, where a large Patagonian toothfish longline fishery operates.

Tracking studies (using satellite transmitters or geolocators–Global Location Sensors; Afanasyev 2004) have provided a good indication of the at-sea distribution of breeding, non-breeding and wintering white-chinned petrel adults from the Crozet Islands and South Georgia (Weimerskirch et al. 1999, Berrow et al. 2000a, Catard et al. 2000, Phillips et al. 2006). In contrast, there is no information for white-chinned petrels

breeding on the Kerguelen archipelago, which hosts the largest population in the southern Indian Ocean (Barbraud et al. 2009), even though this population has been subject to high mortalities during the breeding season due to longline fisheries (Barbraud et al. 2008, Delord et al. 2010). Although most of the waters surrounding the Kerguelen archipelago are regulated under the jurisdiction of the CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources), which is the Regional Fisheries Management Organization (RFMO) for the Southern Ocean, bycatch levels in the Kerguelen EEZ have been extremely high, and are still significant (a few hundred birds per year), despite consistent reduction recently in the number of birds caught (SC-CAMLR 2008, Delord et al. 2010).

When setting conservation goals and priorities in fisheries management in an ecosystemic context, it is important to consider the complex relationships between fisheries and top predators (Cuthbert et al. 2005, Phillips et al. 2006, Copello & Quintana 2009, Fischer et al. 2009, Thalmann et al. 2009, Votier et al. 2010). Understanding the relationship between the at-sea distribution of white-chinned petrels breeding at Kerguelen and of the fisheries operating in the area is, therefore, of primary conservation concern.

Here, we evaluated the extent of home-range overlap between white-chinned petrels breeding at the Kerguelen Islands and 2 longline fisheries: the Patagonian toothfish *Dissostichus eleginoides* longline fishery in the Kerguelen EEZ and the Antarctic toothfish *D. mawsoni* longline fishery further south in the CCAMLR areas. Specifically, the present study addresses the following key questions:

(1) Where do white-chinned petrels forage during the breeding season, and are there fishery vessels operating in the same areas?

(2) At which spatial scale and how accurate should an analysis be to investigate the spatio-temporal overlaps between the at-sea home-range of petrels and longline fishery operations?

(3) Is there any evidence of co-occurrence between breeding petrels and fisheries within the zones of overlap? Does the diet of petrels confirm interactions?

MATERIALS AND METHODS

At-sea distribution of white-chinned petrels during the breeding season. We tracked white-chinned petrel *Procellaria aequinoctialis* breeding adults at the Kerguelen Islands (southern Indian Ocean) during 2 breeding seasons 2005/2006 and 2007/2008 (hereafter referred to as 2006 and 2008; Table 1). Birds just leaving the nest for a foraging trip were captured and fitted

Table 1. *Procellaria aequinoctialis*. Summary of foraging parameters (short and long foraging trips) obtained by platform transmitting terminal (satellite transmitter) deployments during chick rearing in 2006 and during incubation in 2008. Values are given ± SD

Trip type (n)	Trip duration (d)	Maximal range (km)	Distance travelled (km)
Incubation			
Long trips (n = 7)	16.3 ± 1.9	1966 ± 279	10006 ± 1731
Chick rearing			
Long trips (n = 15)	8.9 ± 1.9	1848 ± 171	6382 ± 1626
Short trips (n = 10)	1.1 ± 0.7	253 ± 239	762 ± 641

with satellite transmitters or platform transmitting terminals (PTTs) attached to the feathers on the bird's mid-back (mantle) using waterproof Tesa tape. In 2006, 7 PTTs were deployed between 15 January and 22 February on 14 adults (sex unknown) rearing a chick, leading to 25 foraging trips (9 birds were tracked for multiple trips and 5 for a single trip). In 2008, 7 PTTs were deployed between 17 December and 9 January on 7 incubating adults (3 females, 4 males) for a single trip. We deployed battery-powered and solar Microwave Telemetry PTT 100s (20 g and 12 to 18 g, respectively, i.e. representing 1.2 to 2.3% of the adult body mass, well under the 5% recommended so that equipment does not have adverse effects on bird behaviour; Phillips et al. 2006). Battery-powered PTTs were set to transmit every 60 or 90 s continuously throughout the day, and solar PTTs were duty cycled to 10 h on and 24 h off. As time intervals between transmissions varied greatly (from 1 to 179 min), locations were resampled at 30 min intervals (no assumptions were made about the bird's locations along the track during the 'off' cycle for solar PTTs; BirdLife International 2004), a duration in line with the accuracy of ARGOS (Advanced Research Global Observation Satellite) locations (most locations were in Class 0, i.e. accuracy >1000 m) and bird speed. Unrealistic positions were then filtered using the sda (speed–distance–angle) filter developed by Freitas et al. (2008), without constraint on turning angle and with a maximum mean velocity of 20 m s^{-1} (Catard et al. 2000). This procedure resulted in the retention of 58.4% (n = 4630 locations) of all satellite locations obtained.

Vessels. Fisheries distribution data were obtained by the tracking system of each vessel (GPS), as is requested in the CCAMLR area. The positions and dates of longline sets deployed by licensed demersal longliners targeting toothfish in Statistical Divisions 58.4.1, 58.4.2, 58.4.3a and 58.4.3b (see Fig. 1; referred to as 'southern areas' hereafter) during the period when birds were tracked were provided by the Secretariat of CCAMLR. These fishing vessels were operating in

accordance with CCAMLR's conservation measures, and their data were released under the 'Rules for Access and Use of CCAMLR Data'. Similar data were provided by the PECHEKER database, managed by the 'Ecosystem and Aquatic Population Department' of the National Museum of Natural History in Paris for the French EEZ of Kerguelen (Statistical Division 58.5.1, administrated by the French Southern Territories. Locations of each line were available for the start/end of setting and/or hauling (i.e. 4 positions per set). A fleet of 7 vessels targeted Antarctic toothfish in the southern areas, and the French fleet had a total of 7 vessels targeting the closely related Patagonian toothfish (Appendix, Table A1). This was the total number of vessels licensed for these areas and periods; however, it is likely that other illegal, unreported and unregulated (IUU) fisheries were operating within the area.

Collection of food samples and dietary analysis. The diet of white-chinned petrels breeding at Canyon des Sourcils Noirs was investigated during the chick-rearing period in early March 2005 and 2006. The 55 food samples collected (n = 26 and 29 in 2005 and 2006, respectively) were from large chicks using the water-offloading method (Wilson 1984). Food samples were then drained to remove excess water and kept deep-frozen (–20°C) until diet analysis conducted following Cherel et al. (2000). In brief, each dietary sample was thawed and drained overnight by gravity to separate the solid items from the residual liquid fraction. Subsequently, accumulated items in the solid fraction were sorted, while fresh remains were divided into broad prey classes (fish, cephalopods, crustaceans and others) and were weighed to estimate their proportion of fresh mass in the diet. Since all fresh items showed various levels of digestion, the proportions by mass of prey categories may be biased due to different digestion rates between groups and species. However, the effect is likely minimal in white-chinned petrels, because the few available experimental data showed that the gastric emptying time of procellariiform seabirds does not vary for different food types (Jackson 1992).

Each prey item was counted and identified to the lowest possible taxonomic level using published keys (Baker et al. 1990, Smale et al. 1995, Xavier & Cherel 2009) and our own reference collection. Accumulated cephalopod beaks (beaks with no flesh attached) were analysed separately from fresh items. The abundance of each prey taxon was described by its frequency of occurrence (FO) and numerical importance. FO of a given taxon was calculated as the total number of food

samples containing this taxon relative to the total number of food samples. Numerical importance was calculated as the total number of individuals of a given taxon found in all the samples relative to the total number of all prey items ingested in all the food samples.

Statistical analyses. To investigate overlap between birds and vessels, we determined overall patterns of spatial distribution of bird and vessel locations using fixed kernel home-range utilization distributions (UD; based on Worton 1989). Kernel density analyses have been used successfully to quantify habitat use in numerous studies (e.g. Wood et al. 2000). The UDs provide a probability contour indicating the relative proportion of the distribution within a particular area. The smoothing parameter (h) was estimated using the ad hoc method (Seaman & Powell 1998), and contour levels were estimated for 50, 75 and 95% of the locations. The UDs were calculated weekly from bird and vessel locations.

A common method for quantifying static overlap between individual entities is the percent overlap of home-range outer boundaries (White & Garrott 1990, Kernohan et al. 2001). However, this calculation ignores the relative probability of space-use, i.e. UD, by individuals. Here, we used an overlap index suggested by Fieberg & Kochanny (2005) for quantifying the pattern of space-use as a function of the product of the UDs of overlapping animals: the utilization distribution overlap index (UDOI).

$$\text{UDOI} = A_{\text{seabirds,fisheries}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{U}D_{\text{seabird}}(x,y) \times \hat{U}D_{\text{fisheries}}(x,y)\,dx\,dy \quad (1)$$

where $A_{\text{seabirds,fisheries}}$ is the area of overlap between seabird and fisheries home ranges, and $\hat{U}D_{\text{seabirds}}$ and $\hat{U}D_{\text{fisheries}}$ are the estimated UDs for seabirds and fisheries, respectively, aggregated per calendar week. UDOI is an appropriate index for measuring the degree of space-use sharing, taking into account the degree to which the UDs are concentrated in space (Fieberg & Kochanny 2005). The UDOI equals 0 for 2 home ranges that do not overlap, and it equals 1 if both UDs are uniformly distributed and show 100% overlap. Values of UDOI <1 indicate less overlap relative to uniform space-use, whereas values >1 indicate higher than normal overlap relative to uniform space-use.

We compared the UDOI with a less complex index of home range (HR) that ignores the UD (Fieberg & Kochanny 2005).

$$\text{HR}_{i,j} = \frac{A_{i,j}}{A_i} \quad (2)$$

where $\text{HR}_{i,j}$ is the proportion of home range of seabirds i that is overlapped by the home range of vessels j, A_i is the area of the home range of seabirds i, and $A_{i,j}$ is the area of overlap between the 2 home ranges.

The relationships between UDOI (dependent variable) and spatio-temporal explanatory variables (year, week and zone: EEZ or CCAMLR) were investigated using generalized linear models (GLMs), with a gamma distribution and identity link function. Nonetheless, there was still overdispersion in the data for each analysis (deviance/degrees of freedom >1). Thus, we used an overdispersion coefficient calculated as the ratio of deviance to degrees of freedom (p-scale adjustment). We considered a significance level of 0.05. Model selection was performed using Akaike's information criterion (AIC; Burnham & Anderson 2002), and the model with the lowest AIC was retained. We used GENMOD procedures (SAS Institute 1998–2001) for analysis.

To quantify the association between seabirds and vessels at a higher resolution (i.e. at each location level), we performed dynamic interaction analysis (adapted from Kernohan et al. 2001). The purpose was to estimate the co-occurrence of birds relative to fisheries operating with longline vessels. We therefore created a circle around each location of birds and searched to determine if any longline vessel in operation was simultaneously located within this circle. Because birds and operating vessels were located at specific times (start/end of setting and start/end of hauling for vessels operating in the French EEZ; start/end of setting for vessels operating in other CCAMLR areas), we included a search time window equal to 1 h around the location time of birds (fixed on the time it takes to set a longline). We performed this analysis with a searching circle of radius r incremented as follows: 2, 4, 6, 8, 10, 15 and 20 km (Freeman et al. 2001). This analysis was carried out using locations of longline fishery operations occurring in all sectors prospected by tracked seabirds from Kerguelen to the Antarctic shelf edge. The method could not account for the unknown movements of birds between successive satellite locations, or for the movement of vessels during a day's fishing.

Spatial analyses (including production of kernel and mapping of density distributions), estimations of overlap indices (package *adehabitat*; Calenge 2006) and statistical analyses were performed using R (R Development Core Team 2008) and ESRI ArcGIS Hawths tools (ESRI 1999–2006).

RESULTS

Spatial distribution of white-chinned petrel

White-chinned petrels *Procellaria aequinoctialis* were tracked for 154 d in 2006 during chick rearing and 114 d in 2008 during incubation. While adults trav-
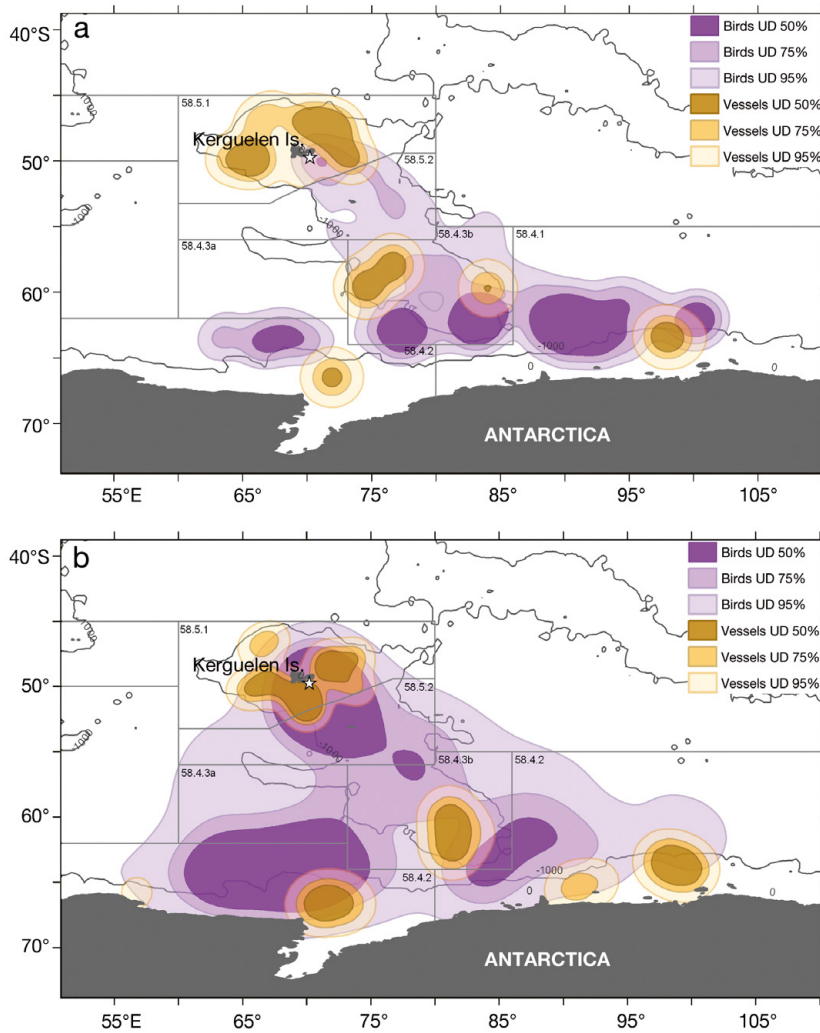
Fig. 1. *Procellaria aequinoctialis*. Overlap of 50, 75 and 95% utilization distributions (UD) of adult white-chinned petrels breeding at Kerguelen with the 50, 75 and 95% UDs of toothfish longline fishing grounds during (a) incubation in 2008 and (b) chick rearing in 2006. The study colony (white star), CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) statistical divisions (grey lines) and bathymetry (m) are shown

sion (2006: 39%; 2008: 11%), the Wilkes Land division (2006: 8%; 2008: 54%) and the BANZARE (British Australian [and] New Zealand Antarctic Research Expedition) bank Subdivision 58.4.3b (2006: 9%; 2008: 35%). The overlap with the Australian EEZ, Heard Island (2006: 19%; 2008: 0%), or the French EEZ (2006: 17%; 2008: 1%) tended to vary between years (i.e. breeding stage). Moreover, tracking has revealed high individual variation in space-use, leading to a large foraging area at the population level (all tracked animals pooled; Fig. 2).

Distribution of fisheries

Locations of operating vessels (setting and hauling) were available for 61 d in 2006 and 49 d in 2008 with, respectively, 22 ± 0.4 and 17 ± 0.2 locations d^{-1}.

Within the CCAMLR areas, longline fisheries targeted Patagonian toothfish in the French EEZ and Antarctic toothfish exclusively in Antarctic waters (Fig. 1). During the study period, 45% of the fishing effort targeted Patagonian toothfish in the French EEZ (exclusively on the shelf break of the Kerguelen plateau), then in the Wilkes Land division (32%; Area 58.4.1) and on BANZARE bank (15%; Area 58.4.3b). In the Antarctic toothfish fishery, effort was focused predominantly on the Wilkes Land division (57%; Area 58.4.1), then on BANZARE bank (28%; Area 58.4.3b) and on Prydz Bay (15%; Area 58.4.2), and also on shelf breaks (Fig. 1). There was no legal fishing in the BANZARE bank subdivision (58.4.3a) during the study period.

elled long distances to Antarctic waters (south of 60°S) during incubation, making only long foraging trips, during the chick-rearing period, they tended to alternate short foraging trips over the Kerguelen/Heard shelf with long foraging trips to Antarctic waters (Table 1, Fig. 1). Overall, during incubation and chick rearing, they spent a higher proportion of time in Antarctic waters than in the French EEZ (only short trips). During incubation in 2008, 99% of the total surface of the core area (UD at 50%) was located in Antarctic waters versus 1% in the French EEZ, while, during chick rearing in 2006, 17% was located in the French EEZ and 83% in the southern areas. The core area tended to overlap mainly with the Prydz Bay divi-

Overlap between petrels and fisheries

The proportion ($HR_{i,j}$) of the home range of adult white-chinned petrels (HR index) that was overlapped by longliners was small (Fig. 3). The overlapping zones appeared to vary among areas — HR was higher in the French EEZ than in southern areas — and between breeding stages — HR was higher during chick rearing in 2006 than during incubation in
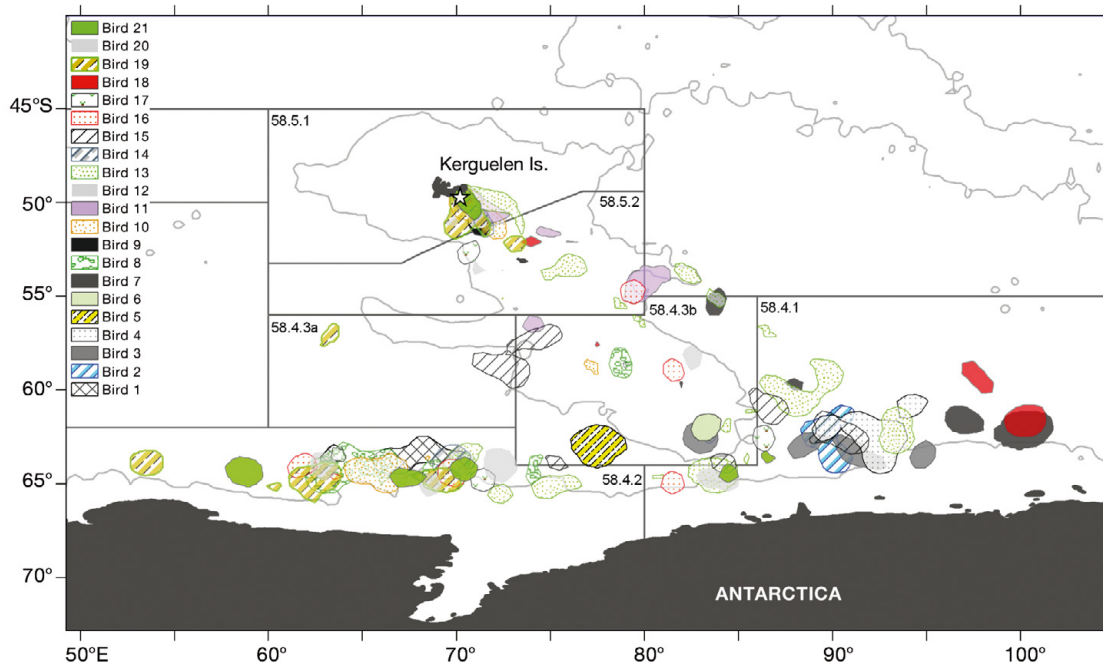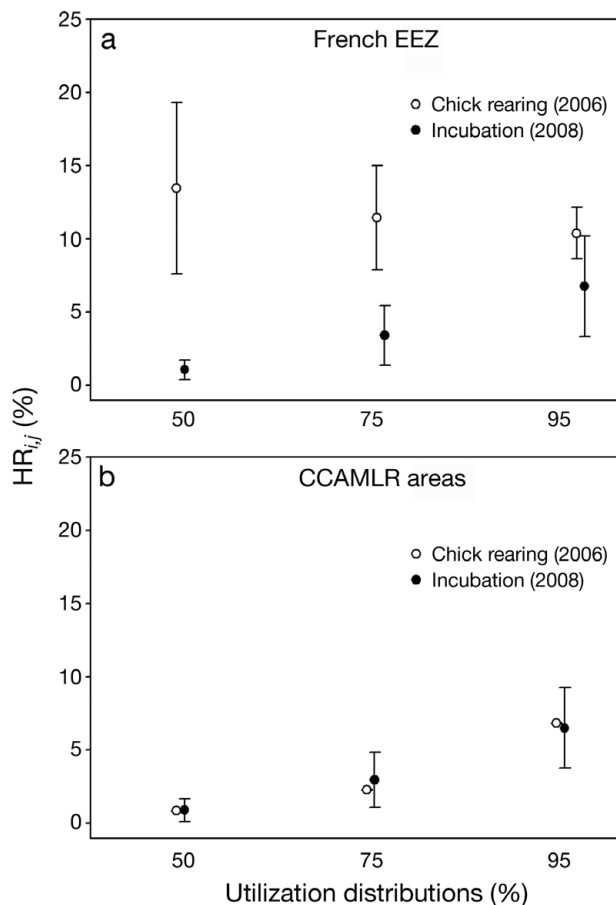
Fig. 2. *Procellaria aequinoctialis*. Core area (50% utilization distributions) of each of the tracked white-chinned petrel adults (n = 21) breeding at Kerguelen, during incubation in 2008 and during chick rearing in 2006. The study colony (white star) at Kerguelen Island and the CCAMLR statistical divisions (grey lines) are shown

2008 in the French EEZ. Accordingly, the UDOIs of home ranges of adult white-chinned petrels that overlapped with the home ranges of legal toothfish longliners indicate relatively small values of overlap (<1; Fig. 4). The UDOI between breeding birds and vessels did not vary significantly according to year, week, or zone (Table 2). Nevertheless, the UDOI (considering 95% UD) tended to be higher within the French EEZ (0.03 ± 0.05) than in the southern areas (0.01 ± 0.02) (p = 0.18). The highest overlap (0.07 ± 0.07) was obtained during chick rearing (in 2006), compared to 0.01 ± 0.02 during incubation (in 2008) for the French EEZ (p > 0.05), while no trends appeared for the southern areas (Fig. 4). These results suggest that overlap areas of breeding birds and vessels were not uniform and that specific areas were used differently depending on the breeding stage and/or the zone within the overlap areas.

Fig. 3. *Procellaria aequinoctialis*. Mean (±SE) proportion (HR$_{i,j}$) of the home range of adult white-chinned petrels i that is overlapped by the home range of longliners j (targeting Antarctic toothfish within the CCAMLR Statistical Divisions 58.4.1, 58.4.2 and 58.4.3b and Patagonian toothfish within the French EEZ statistical division 58.5.1). Panels illustrate the proportions of conditional 50, 75 and 95% utilization distributions (percent) for the (a) French EEZ and (b) other CCAMLR areas during chick rearing and incubation (2006 and 2008, respectively)
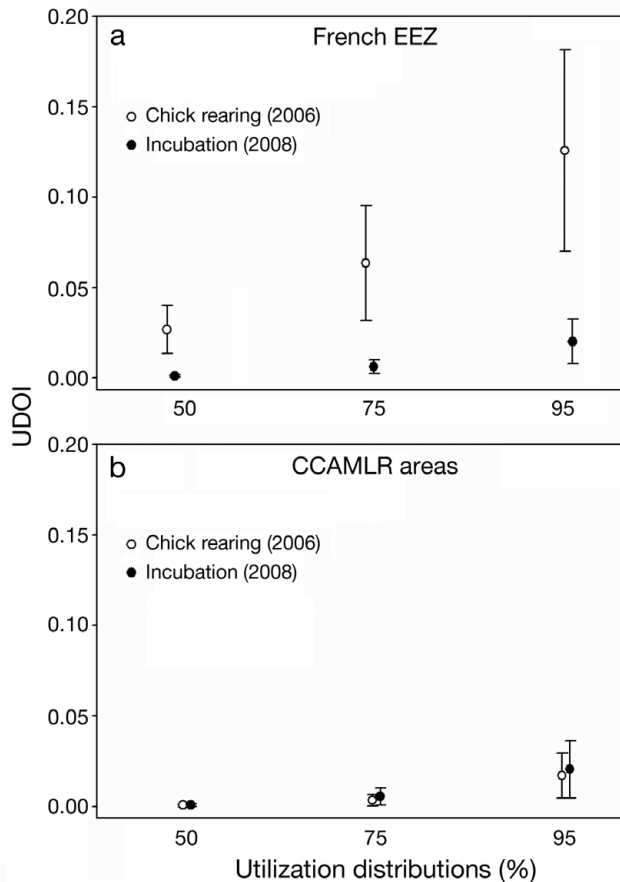
Fig. 4. *Procellaria aequinoctialis*. Mean (±SE) utilization distribution overlap index (UDOI) between adult white-chinned petrels and longliners (targeting Antarctic toothfish within the CCAMLR Statistical Divisions 58.4.1, 58.4.2 and 58.4.3b). Panels illustrate the proportions of conditional 50, 75 and 95% utilization distributions (percent) for the (a) French EEZ and (b) other CCAMLR areas during chick rearing and incubation (2006 and 2008, respectively)

The overlap estimated by dynamic analysis between birds and legally operating vessels revealed that potential co-occurrence and/or association with longliners was infrequent during the study period (Table 3). A total of 4 birds were found to overlap with 3 different vessels, mainly during the chick-rearing period (2 in the French EEZ and 1 in the southern areas; Fig. 5). Within a 15 km and 1 h range, only 1 bird was associated with a single vessel in the French EEZ (Fig. 5b). The same vessel was potentially involved in associations within the EEZ with 2 different birds at different times (Fig. 5b,c). Birds co-occurred in the vicinity of vessels during setting (2), as well as hauling (2), and during the departure from the colony (2), as well as on the way back (2). No overlap occurred between birds and vessels at lower distance intervals. The co-occurrence rose slightly within a 20 km radius. The data do not allow quantification of the duration of the overlap between birds and vessels, due to limitations in both the temporal resolution of satellite transmitters and the accuracy of Argos.

Diet

The mean mass of the solid fraction of the stomach samples was 85 g, including 80 g of fresh items and 5 g of accumulated items (mainly vegetable matter and cephalopod beaks). Anthropogenic items (3 plastic particles, 1 bottle label and 1 small piece of fishing line) were found in 5 samples. Overall (i.e. all 55 samples pooled), chick food was dominated by fish, accounting for 66% by fresh mass of the diet. Other significant food sources were cephalopods (17% by mass) and crustaceans (12%). White-chinned petrels fed less on cephalopods in 2005 than in 2006 (8 and 25%, respectively) (Table 4).

Table 2. *Procellaria aequinoctialis*. Models of variation in the utilization distribution overlap index for measuring the degree of space-use sharing between seabirds and fisheries, estimated by generalized linear models as a function of covariates. Selected model in **bold**

Model	Deviance	No. of parameters	AIC
Constant	33.57	2	35.57
Year	31.86	3	37.86
Zone	**27.08**	**3**	**33.08**
Year + Zone + Year × Zone	24.26	9	42.26
Year (week)	13.59	11	34.59

Table 3. *Procellaria aequinoctialis*. Summary of dynamic interaction analysis to estimate co-occurrence, for the searching circle of incremented radius *r* (in km) (see 'Materials and methods'), between breeding white-chinned petrels and operating toothfish longline vessels during bird-tracking periods in 2006 and 2008. EEZ: Exclusive Economic Zone; CCAMLR: Commission for the Conservation of Antarctic Marine Living Resources

Area	No. of bird locations associated with operating vessels			Total no. of locations analysed
	<15 km	15 km	20 km	
French EEZ[a]	0	1	3	626
CCAMLR (other areas)[b]	0	1	1	1870

[a]EEZ of Kerguelen
[b]Statistical Divisions 58.4.1 (Wilkes land), 58.4.2 (Prydz Bay), 58.4.3b (BANZARE bank) and 58.5.2 (Australian EEZ)
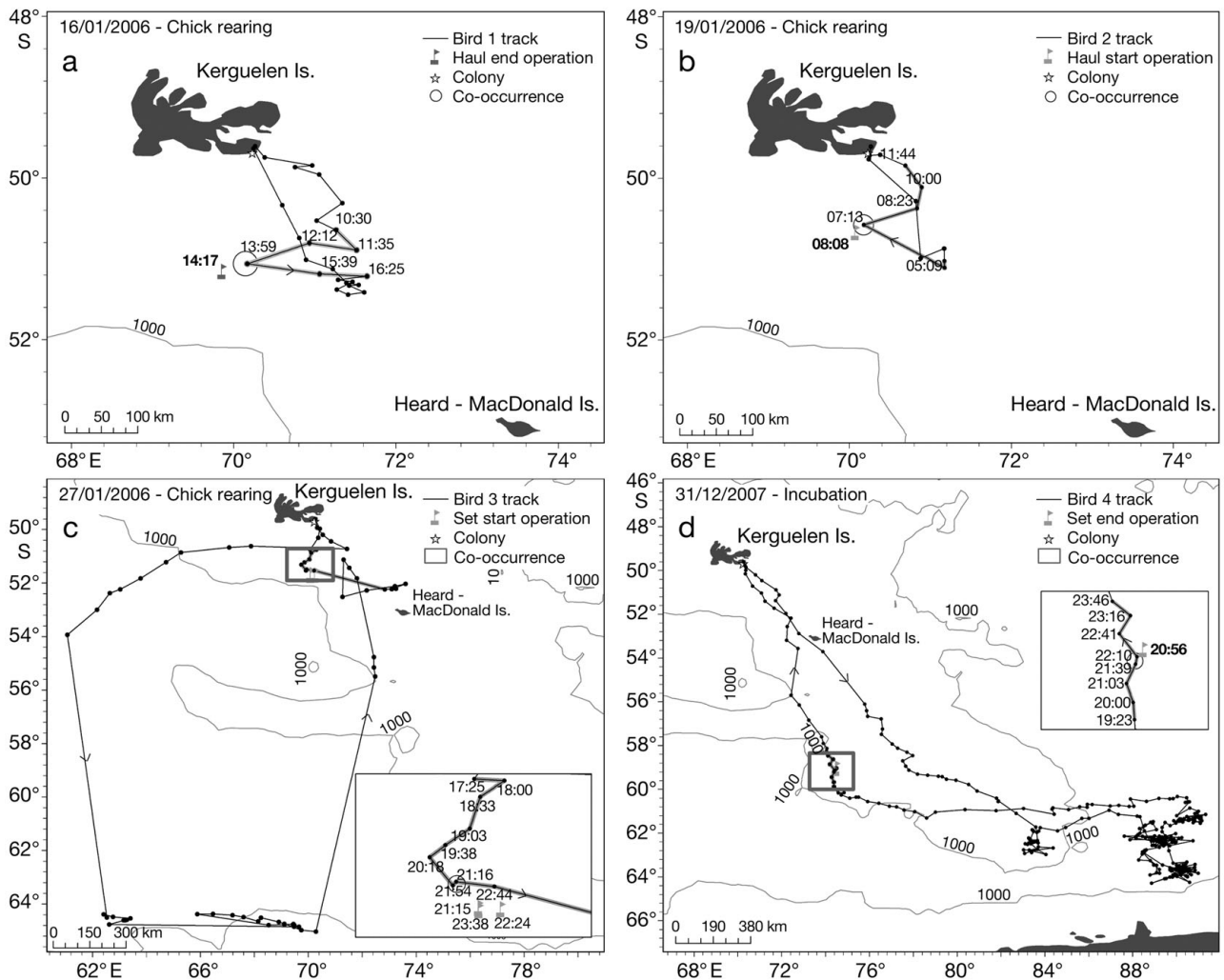
Fig. 5. *Procellaria aequinoctialis*. Foraging tracks of breeding white-chinned petrel adults (n = 4) that co-occurred with legal toothfish longliners at the (a) end of hauling, (b) start of hauling, or (c) start of setting during the chick-rearing period (2006) in the French EEZ and (d) at the end of setting during the incubation period (2008) in CCAMLR Area 58.4.3b. Locations of birds (black dot) and of operating vessels (grey flag), and corresponding times are reported

Table 4. *Procellaria aequinoctialis*. Mean (±SD) mass and composition of the stomach food contents of white-chinned petrel chicks from the Kerguelen Islands

Diet component	2005 (n = 26)	2006 (n = 29)	Total (n = 55)
Items by weight (g)			
Solid fraction	85.9 ± 37.4	84.3 ± 41.9	85.0 ± 39.5
Accumulated items	5.6 ± 4.1	3.9 ± 3.4	4.7 ± 3.8
Fresh items	80.3 ± 36.5	80.4 ± 41.4	80.3 ± 38.8
Fish	57.0 ± 46.0	50.1 ± 41.4	53.4 ± 43.4
Cephalopods	6.7 ± 15.7	20.5 ± 34.8	13.9 ± 28.1
Crustaceans	11.3 ± 21.2	8.8 ± 20.0	9.9 ± 20.4
Others	5.3 ± 18.6	1.1 ± 4.5	3.1 ± 13.2
Overall composition of fresh items (% by weight)			
Fish	71.0	62.3	66.4
Cephalopods	8.3	25.4	17.4
Crustaceans	14.0	10.9	12.4
Others	6.6	1.3	3.8

A total of 2780 fresh prey items from 43 species or prey categories were recovered from the 55 dietary samples (Table 5). Items included 2616 (94%) crustaceans, 86 (3%) fishes and 66 (2%) cephalopods. Crustaceans occurred in all samples and dominated the diet by number, but, owing to their small size, they were much less important by mass. By far, the 2 main crustacean species were the Antarctic krill *Euphausia superba* and the hyperiid amphipod *Themisto gaudichaudii* (70 and 21% of the total numbers of prey, respectively).

Fish and cephalopods occurred in 85 and 53% of the dietary samples, respectively (Table 5). White-chinned pe-

Table 5. *Procellaria aequinoctialis*. Frequency of occurrence and numbers of main prey items identified from stomach contents of white-chinned petrel chicks at the Kerguelen Islands (total for all 55 samples pooled)

Species	Occurrence		Number		Fishery-related item?
	(n)	(%)	(n)	(%)	
Fish	**47**	**85.5**	**86**	**3.1**	
Clupeidae					
Sardinops sp.	2	3.6	3	0.1	Yes (bait)
Paralepididae					
Magnisudis prionosa	18	32.7	18	0.6	No
Notolepis coatsi	7	12.7	13	0.5	No
Myctophidae spp. (6 species)	10	18.2	12	0.4	No
Macrouridae					
Coryphaenoides lecointei	7	12.7	7	0.3	No (possibly?)
Macrourus carinatus/holotrachys	8	14.5	9	0.3	Possibly (bycatch)
Unidentified macrourids	6	10.9	6	0.2	Possibly (bycatch)
Gempylidae					
Paradiplospinus gracilis	3	5.5	3	0.1	No
Osteichthyes spp. (8 species)	9	16.4	10	0.4	No
Unidentified fishes	5	9.1	5	0.2	
Cephalopods	**29**	**52.7**	**66**	**2.4**	
Ommastrephidae					
Todarodes sp.	5	9.1	6	0.2	No
Brachioteuthidae					
Slosarczykovia circumantarctica	15	27.3	42	1.5	No
Oegopsida spp. (4 species)	6	10.9	6	0.2	No
Unidentified squid	10	18.2	12	0.4	No
Crustaceans	**55**	**100.0**	**2616**	**94.1**	
Euphausiacea					
Euphausia superba	46	83.6	1940	69.8	No
Euphausia sp.	6	10.9	8	0.3	No
Caridea					
Pasiphaea scotiae	18	32.7	22	0.8	No
Mysida					
Neognathophausia gigas	3	5.5	3	0.1	No
Amphipoda					
Themisto gaudichaudii	28	50.9	592	21.3	No
Eurythenes gryllus/obesus	7	12.7	7	0.3	No
Copepoda					
Sarcotretes eristaliformis	13	23.6	22	0.8	No
Other parasitic copepods (4 species)	7	12.7	16	0.6	Possibly
Crustacea spp. (5 species)	5	9.1	6	0.2	No
Others	**6**	**10.9**	**12**	**0.4**	
Unidentified carrion	6	10.9	12	0.4	No (possibly?)
Total			**2780**	**100**	

trels fed on a large variety of fish (20 taxa). At the family level, the diet was dominated by oceanic paralepidids and myctophids, and by deep-sea macrourids. The clupeid *Sardinops* sp. was found in 2 chick food samples in 2006; the species does not occur in the area and is known to be used as bait on longliners (especially by vessels using the Spanish system in CCAMLR areas). The diet analysis allowed us to estimate that fishery-related items occurred in 3.6, 21.8 and up to 38.2% of samples (cf. Table 5), depending on whether we consider only species used as bait (*Sardinops* sp.), probable bycatch species associated with fishery operations (macrourids sp. and *Macrourus carinatus/holotrachys*), or deep-sea species that are normally not available to the birds (*Coryphaenoides lecointei*) (see 'Discussion').

Two cephalopod species occurred in significant numbers in food samples: the brachioteuthid *Slosarczykovia circumantarctica* and the ommastrephid *Todarodes* sp. (Table 5). Analysis of a much larger number of beaks (n = 343) that had accumulated in chicks' stomachs showed a more diverse cephalopod diet, including 14 different species of squids and 1 species of octopus (Appendix, Table A2). Accumulated beaks nevertheless confirmed the predominance of *S. circumantarctica* (51% of the total number of beaks) and of *Todarodes* sp. (11%) in the petrel diet. Other significant prey species included the gonatid *Gonatus antarcticus* (10%) and the histioteuthid *Histioteuthis eltaninae* (6%).

DISCUSSION

At-sea distribution of Kerguelen white-chinned petrels

White-chinned petrels *Procellaria aequinoctialis* breeding at Kerguelen foraged mainly in Antarctic waters (south of the Antarctic Circumpolar Current Front, 60°S). During chick rearing they alternated short foraging trips targeting the Kerguelen/Heard shelf with long foraging trips to Antarctic waters, yet they invested most of their foraging time in Antarctic waters. Crozet white-chinned petrels also alternated between short and long foraging trips during the chick-rearing period (Catard et al. 2000). However, during the long trips of the incubation period, unlike Kerguelen birds, Crozet birds did not forage in Antarctic waters, but remained in sub-Antarctic or sub-tropical waters. White-chinned petrels breeding at South Georgia (southern Atlantic Ocean) fed on krill to a greater extent than at other locations. They foraged mainly in sub-Antarctic and Antarctic waters, utilizing the Argentine-Patagonian shelf, South Georgia/Shag Rocks and the area south to the South Orkney Islands (Berrow et al. 2000a). White-chinned petrels fed as often in cold oceanic waters and on the nearby neritic slope as in warm subtropical areas (Berrow et al. 2000a, Catard et al. 2000, Phillips et al. 2006, Weimerskirch et al. 1999).

Estimating overlap between petrels and fisheries

White-chinned petrels breeding at Kerguelen travelled across the 5 CCAMLR Statistical Divisions situated south of the French EEZ. All tracked birds remained largely outside the French EEZ, except during short foraging trips. Nonetheless, the French EEZ represents an obligate corridor for a central place forager travelling between Kerguelen and Antarctic waters (Matthiopoulos 2003, Fagan et al. 2007).

Obtaining accurate estimates of overlap between seabirds and fisheries requires addressing the issue at a pertinent spatial and temporal scale. This topic has received attention only recently and mainly through the measure of overlap between the at-sea distribution of seabirds (kernel contours or location data) and fishing effort/catch (number of hooks set per year, average annual fishing effort or total catch; Cuthbert et al. 2005, Phillips et al. 2006, Copello & Quintana 2009, Fischer et al. 2009). Only a few studies have analysed associations at a finer temporal or spatial scale: bird tracks overlaid on sanctioned sets or summarized by grid squares based on setting locations (Freeman et al. 2001, Nel et al. 2002a, Petersen et al. 2008, Trebilco et

al. 2008, Thalmann et al. 2009) and investigation of behavioral responses using GPS tracking and the vessel monitoring system (VMS; Votier et al. 2010).

When analysing data on the breeding season level at a large scale, we found spatio-temporal overlap between white-chinned petrel foraging grounds and longline fishing grounds. As the foraging areas targeted by birds included several large (partly due to inter-individual variability in space-use) and productive areas, this inevitably resulted in overlap with vessels. The changes in foraging patterns between incubation and chick-rearing periods resulted in a shift in the spatial overlap. Consequently, this implied that interactions may happen with spatially distant longline fisheries (i.e. operating in Antarctic waters) or with fisheries operating in nearby areas, depending on the breeding stage.

HR and UDOI quantified the overlap between birds and vessels (on a weekly level) and globally showed the same trends. The overlap indices tended to increase with increasing UD contours, being higher when considering the 95% kernel UD. The overlap between birds and vessels tended to be higher in the French EEZ than in southern areas. Here, birds possibly faced a higher interaction probability due to higher fishing efforts concentrated over a more restricted area (cf. Appendix, Table A1). Furthermore, overlap was higher during chick rearing (in 2006) than during incubation (in 2008), suggesting a stage-specific probability of interaction. Although HR can be applied to home-range estimates, it can lead to overestimation of spatial overlap by ignoring patterns of use within the confines of the outer home-range boundary (Kernohan et al. 2001). UDOI seems to be a more suitable index, indicating less overlap relative to uniform space-use (uniformly distributed and 100% overlap).

Dynamic analysis of co-occurrence explored, at a smaller spatial and temporal scale, the reality behind the estimates of overlap quantified by the static spatial analysis (HR and UDOI). Consistently, we found that overlap between birds and vessels occurred more often in the French EEZ and predominantly during the chick-rearing period. However, a few instances of spatio-temporal co-occurrence between birds and vessels were detected and tended to occur around the Kerguelen/Heard shelf. This could easily be associated with the typical infrequent and clustered distribution of the incidental bycatch phenomenon (Delord et al. 2010). Observations revealed that at least 4 birds out of 21 may have co-occurred with fishing vessels, but our data do not permit us to judge whether birds were close enough to directly interact with fishing gear. Our analysis does permit us to quantify co-occurrence, i.e. when birds and vessels were at the same place more or less at the same moment (this

means that birds could be in movement and not necessarily interact with vessels), but gave no direct evidence that an interaction occurred, which can be seen as a limitation of this approach. The co-occurrence happened during both hauling and line setting. Nevertheless, the accuracy of the locations of birds (Argos mean accuracy >1000 m for these data) and the fact that we only have access to sporadic locations (set and haul start/end) for operating vessels could lead to underestimation of bird–vessel interactions. The use of an activity register logger, such as a geolocator, coupled with a satellite transmitter should be useful in providing information on activity patterns, which can aid in detecting the behavioural changes in birds when they are in the vicinity of operating vessels. The analysis of concurrent GPS tracking data for birds and VMS data for vessels permits further investigation of the primary questions concerning scavenging behaviour and an estimation of interactions at a very fine scale (Votier et al. 2010). Our results underlined the fact that the use of different analytical methods (at various spatial and temporal scales) highlights the mismatch between high large-scale overlap and low small-scale co-occurrence. This approach permits the estimation of overlap between birds and fisheries and provides multiple levels of interpretation despite these limitations. It is invaluable for conservation and management decisions, as it identifies important areas for birds, at-risk zones and corridors on a large spatial scale, as well as assessing the heterogeneity of co-occurrence risks for birds.

Dietary relationships with fisheries

White-chinned petrels from the Kerguelen Islands mainly fed their chicks with fish, but cephalopods and crustaceans were also important foods. These findings are in broad agreement with other analyses of diet conducted for localities in the southern Indian Ocean, such as Marion (Cooper et al. 1992) and the Crozet Islands (Ridoux 1994, Catard et al. 2000, Connan et al. 2007), but contrasts with results for South Georgia, where crustaceans were the main prey by mass (Berrow & Croxall 1999). Indeed, Antarctic krill are abundant in the waters of South Georgia, but do not occur in the waters surrounding Marion, Crozet and the Kerguelen Islands. Hence, the presence of Antarctic krill in food samples is indicative of long foraging trips south of the breeding colonies down to Antarctic waters (Catard et al. 2000, present study).

A remarkable feature of the diet of white-chinned petrels at the Kerguelen Islands was the importance of deep-sea macrourid fishes; 22 macrourids were found in the 20 samples of stomach contents (36% of the total

number of samples) collected in 2005 and 2006. Macrourids are generally a rare prey of seabirds from the Southern Ocean (Cherel & Klages 1998, but see Richoux et al. 2010). However, the macrourid *Coelorinchus fasciatus* constitutes the main fish prey of white-chinned petrels on their wintering grounds in the Benguela region (Jackson 1988), where this fish is taken in considerable quantities as bycatch by commercial trawlers (Cohen et al. 1990). Since white-chinned petrels have been reported to be frequently associated with fishing vessels (Weimerskirch et al. 2000), the most likely explanation is that they fed on *C. fasciatus* discarded by the fishery. In the same way, *Macrourus carinatus/holotrachys* is the most common bycatch of longliners operating in Kerguelen waters (Duhamel et al. 2005), potentially explaining the occurrence of these species in seabird food samples (Cherel et al. 2000, 2002, present study). The dietary presence of other macrourids is more puzzling, because species of the genus *Coryphaenoides* inhabit deep waters (1500 to 5000 m depth; Gon & Heemstra 1990, Duhamel et al. 2005) in the Southern Ocean, where they are unavailable to both seabirds and commercial fisheries. As previously mentioned (Cherel et al. 2000), the way albatrosses and petrels catch some of their benthic and deep-sea prey remains a mystery in some respects and requires further investigation.

The occurrence of *Sardinops* sp. in food samples is a clear indication of dietary relationships between breeding white-chinned petrels and commercial fisheries. Sardines are commonly used as bait on longliners targeting the Patagonian toothfish, and have been previously found in the diet of white-chinned petrels from the Crozet Islands (Catard et al. 2000). Whereas no fishery-related dietary items (bait, discards, or offal) were identified in food samples collected in the beginning of the 1980s, when fisheries did not operate in the southern Indian Ocean (Ridoux 1994), they were found in the majority of food samples collected at the end of the 1990s, when a considerable number of illegal longliners were operating in Crozet and Kerguelen waters (Catard et al. 2000). The lower frequency of such items in more recent years may be related to the sharp decline in the number of longliners fishing in the area (Connan et al. 2007, present study). Fishery-related items found were mainly discards and not bait, indicating that birds were not entirely at-risk of being hooked while attending longliners.

As birds and fisheries target prey of different species and/or sizes, competition for the same prey during the breeding period can be ruled out. Indeed, birds target crustaceans, fish and cephalopods and do not dive deeper than 12 m (Huin 1994), whereas longliners target toothfish and seldom operate at a depth shallower than 500 m.

Implications for management and conservation

Spatio-temporal overlap between birds and fisheries — considered to reflect the incidental mortality risk faced by the birds — is a necessary precondition for interactions and/or bycatch. However, it is not necessarily a good predictor of bycatch at the local (i.e. vessel) scale (Hamel et al. 2008). Estimates of overlap enable the determination of areas of higher bycatch risk and, thus, contribute to monitoring surveys and the implementation of mitigation measures on the Heard-Kerguelen Islands shelf and the connected Antarctic shelf. For example, overlap can be used to determine 'no-take' areas for fisheries at certain stages in the breeding cycle of white-chinned petrels (Delord et al. 2010).

White-chinned petrel remains among the most common and most difficult species to protect from bycatch, due to their wide foraging range, diet and diving abilities (Delord et al. 2005, 2010, Moreno et al. 1996, 2006, Murray et al. 1993, Nel et al. 2002b, Robertson et al. 2006, Petersen, et al. 2007). The incidental mortality reported for legal longliners in the French EEZs — particularly in the Kerguelen EEZ — is the highest among in the CCAMLR statistical divisions (SC-CAMLR 2008) and, in recent years, has posed a recurrent problem (Delord et al. 2005), although, globally, the situation has improved since the early 2000s, with a decline in the bycatch of white-chinned petrels from at least 15 000 birds in 2003 to 300 in 2009 (Delord et al. 2005, 2010). Recent efforts at mitigation measures (e.g. use of bird-scaring lines, improvement of the line-sink rate, closing during specific periods) and extended dialogue between interested parties (national administrations, the fishing lobby, fishing masters and scientists) were obviously efficient in reducing bycatch (Delord et al. 2005, 2010).

Recoveries of bands in longline fisheries remain anecdotal (Barbraud et al. 2008) and do not allow estimates of fishery-induced mortality (Delord et al. 2005) and its impact on population dynamics. In addition, these recoveries only pertain to populations breeding at Crozet, where demographic studies have been carried out for the last 25 yr and for which incidental captures occurred by longline or trawl vessels of both the hake and tuna fisheries in the Benguela Current System (Weimerskirch et al. 1999, Catard et al. 2000, Ryan et al. 2002) and of the Patagonian toothfish fishery in the French EEZ of Crozet (CCAMLR Statistical Division 58.6). No data are available for the white-chinned petrel population at Kerguelen, but there is a growing body of evidence for declining populations at South Georgia and Crozet over the last few decades (Barbraud et al. 2008, 2009, Berrow et al. 2000b) and for a decline of at-sea densities in the Prydz Bay area (Woehler, 1996) and in the southern Indian Ocean (Péron et al. 2010). Nonetheless, a recent demographic study demonstrates the combined negative effects of longline fisheries and climate on the population of white-chinned petrel at Crozet (Barbraud et al. 2008).

Our results on breeding white-chinned petrels (diet and tracking analyses) indicate that overlap with legal toothfish longliners occurred, and was concentrated mainly within the French EEZ: 19 % of birds co-occurred in the vicinity (within 20 km) of longliners, and 4 to 22 % of chicks had ingested prey related to longline vessels (cf. Table 5). Zones located off the EEZ south/southwest of the colony could be considered at-risk as obligate corridors.

If we consider that a minimum of 19 % of the studied breeding birds were attending longliners directly, a quick calculation based on the population size and breeding success of the species (Barbraud et al. 2008, 2009) suggests that as many as 56 000 breeding birds out of the 1 to 1.7 million individuals in the Kerguelen population (Barbraud et al. 2009) may have attended longliners, if birds originating from other colonies at Kerguelen have similar foraging grounds to that of our study colony. The magnitude of potential interactions we found can, therefore, explain the large number of birds attending longliners and the level of bycatch observed for the French EEZ in the early 2000s.

In addition, diet analysis for white-chinned petrels showed that interactions between breeding birds and vessels in other areas and possibly with the IUU fishery do occur. Although fishing is well-regulated under the jurisdiction of the CCAMLR (Croxall & Nicol 2004), other fishing operations in the CCAMLR area include a recently developed and large IUU fishery for Antarctic toothfish. Furthermore, the problem area has moved, particularly to the international high-seas area of BANZARE bank (Tuck et al. 2003, SCIC-CAMLR 2007, SC-CAMLR 2008). Moreover, a number of IUU vessels seem to have converted to gillnetters, shifting their efforts to high-sea areas and oceanic banks and targeting species such as toothfish, grenadiers, squid and crabs (SCIC-CAMLR 2007). For decades gillnet fisheries have been identified as one of the largest producers of bycatch (see Tasker et al. 2000 for review); this shift might therefore represent a present-day and future conservation concern for the southern high seas.

The identification of factors driving the distribution of birds and/or their prey could be used in determining areas of overlap among fisheries and species of conservation concern and in forecasting areas of likely fishery–bycatch interactions (Lewison et al. 2009). It is particularly vital to maximize the efficiency of management strategies, by identifying multispecies bycatch areas and categorizing marine important bird areas (Game et al. 2009).

CONCLUSIONS

White-chinned petrels from the Kerguelen Islands overlap with longline fisheries at a large spatial and temporal scale and co-occur at a small scale.

Similarly, the presence of fishery-related items in the diet of petrels suggests that the use of fisheries is not negligible (at least 4 %, perhaps more). These results emphasize a certain amount of mismatch with regard to overlap level depending on the method of analysis used and support the combination of complementary approaches. Such analysis suggests that white-chinned petrels and fisheries occupy the same overall zone, but only a small percentage of the population is likely to interact with fisheries within the area. However, even if the birds attending longliners represent a small proportion of the Kerguelen population, since the population is huge, this small proportion represents 10s of 1000s of birds at risk. Consequently, management authorities should maintain and implement strict mitigation measures to further reduce bycatch.

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Table A1. *Procellaria aequinoctialis.* Summary of the toothfish longline fishery during bird tracking in 2006 and 2008. CCAMLR: Commission for the Conservation of Antarctic Marine Living Resources; EEZ: Exclusive Economic Zone; BANZARE: British Australian and New Zealand Antarctic Research Expedition

No. of vessels	CCAMLR statistical division	Sector	Fishing effort (no. of hooks set)	No. of sets	Mean (range) duration of fishing trip (d)
2006					
5	58.4.1	Wilkes land	1 862 826	198	16 (1–33)
3	58.4.2	Prydz Bay	659 435	94	11 (6–16)
4	58.4.3b	BANZARE bank	1 361 725	96	13 (1–32)
6	58.5.1	French EEZ[a]	2 567 793	287	18 (16–22)
0	58.5.2	Australian EEZ[b]	0	0	–
2008					
6	58.4.1	Wilkes land	2 178 176	268	18 (4–33)
1	58.4.2	Prydz Bay	388 500	33	17 (17)
2	58.4.3b	BANZARE bank	589 800	108	19 (9–29)
6	58.5.1	French EEZ[a]	3 199 438	346	22 (19–23)
0	58.5.2	Australian EEZ[b]	0	0	–

[a]EEZ of Kerguelen
[b]Australian EEZ longline season from April to September each year

Table A2. *Procellaria aequinoctialis.* Cephalopod diet (both accumulated upper and lower beaks) identified from stomach contents of white-chinned petrels during chick rearing at the Kerguelen Islands (total for all 55 samples pooled)

Species	Number of items (n)	(%)
Ommastrephidae		
Todarodes sp.	28	11.3
Onychoteuthidae		
Moroteuthis knipovitchi	4	1.6
Moroteuthis sp. B (Imber)	2	0.8
Kondakovia longimana	9	3.6
Psychroteuthidae		
Psychroteuthis glacialis	1	0.4
Brachioteuthidae		
Slosarczykovia circumantarctica	127	51.2
Gonatidae		
Gonatus antarcticus	24	9.7
Histioteuthidae		
Histioteuthis eltaninae	15	6.0
Histioteuthis macrohista	1	0.4
Neoteuthidae		
Alluroteuthis antarcticus	1	0.4
Mastigoteuthidae		
Mastigoteuthis psychrophila	9	3.6
Batoteuthidae		
Batoteuthis skolops	6	2.4
Cranchiidae		
Galiteuthis glacialis	11	4.4
T aonius sp. B (Voss)	9	3.6
Octopodidae		
Octopodidae sp.	1	0.4
Total	248	100.0
Unidentifiable beaks (eroded)	95	