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Estimates of population size of white-chinned petrels and grey petrels at Kerguelen Islands and sensitivity to fisheries

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Abstract

White-chinned petrels *Procellaria aequinoctialis* and grey petrels *Procellaria cinerea* are among the most frequently killed seabird species by accidental bycatch, and both species have received strong conservation concern. Data on population size are required to evaluate the impact of bycatch and to establish management plans. We estimated the population size of both species at Kerguelen, Southern Indian Ocean, from 2004 to 2006 by explicitly taking into account detection probability of burrows using distance sampling and burrow occupancy. A total of 31 line-transects were distributed across the eastern part of Kerguelen, representing a total length of 566 km. Detectability was low (from 0.19 to 0.54 for white-chinned petrels, 0.58 for grey petrels). Burrow densities varied from 1.37 ± 0.67 to 25.77 ± 5.23 burrows ha^{-1} for white-chinned petrels and was 2.78 ± 0.79 burrows ha^{-1} for grey petrels. For white-chinned petrels, these densities were extrapolated to the entire surface area of vegetation and there were 234 000 (186 000–297 000) active burrows on Kerguelen. For grey petrels, the number of active burrows for the eastern part of Kerguelen was 3400 (1900–5600). Based on these estimates, the potential biological removal method suggests that the additional mortality on birds caused by the fisheries operating around Kerguelen can be considered a serious threat for the species at least at the regional scale of the Southern Indian Ocean, especially for grey petrels.

Introduction

Several populations of albatrosses and petrels are affected by global changes such as fisheries bycatch, introduced predators or climate change (Brooke, 2004), and estimates of population size from surveys are a crucial tool for understanding the population dynamics and setting conservation priorities for these species. Yet, apart from most albatross species, there are few robust estimates of population sizes of petrels (Brooke, 2004) because most are nocturnal burrowing species being at sea most of the year (Warham, 1990), which makes them difficult to survey. In addition, to our knowledge, very few studies have taken into account the detection probability (or detectability) of these species in estimating their abundance on their breeding grounds (Lawton *et al.*, 2005; Robertson *et al.*, 2008). Detection probability is the probability of missing an individual (or a burrow for studies that estimate a number of burrows as a proxy for the number of breeding pairs) given it is present in the sampling area, which is likely to be lower than one for relatively small burrowing species. Not taking into account detectability may lead to serious biases in estimates of abundance (Williams, Nichols & Conroy, 2002), and therefore to mislead conservation status and priorities.

The white-chinned petrel *Procellaria aequinoctialis* and the grey petrel *Procellaria cinerea* are large burrowing seabirds of the Southern Ocean (respectively, ~1350 and ~1000 g). White-chinned petrels breed during the austral summer from November (egg laying) to April (fledging) and feed on fish, cephalopods, krill and occasionally offal, whereas grey petrels breed during the austral winter from March to late September–early December and mainly feed on squid, fish and occasionally offal (O'Brien, 1990; Rogers, 1990; Brooke, 2004). Both species are long-lived and lay only one egg per year (Warham, 1990). The white-chinned petrel is the most frequently killed seabird species in the Southern Ocean by accidental bycatch (Weimerskirch *et al.*, 2000; Delord *et al.*, 2005; Robertson *et al.*, 2006), and the species was moved from an IUCN listing of lower risk/near threatened to vulnerable in 2000 (Birdlife International, 2000). Although it is estimated that more than two to three million pairs are breeding worldwide (Brooke, 2004) detailed complete surveys are lacking on the major breeding grounds, and previous estimates are out of date and did not take into account detection probability. Although being listed as lower risk/near threatened (Birdlife International, 2000), the grey petrel is also a frequent victim of longline fisheries (Bartle, 1990; Robertson & Bell, 2002). Current estimates of its breeding populations are very imprecise (Brooke, 2004) and, due to its winter-breeding habit the impact of introduced predators is exacerbated since they often have few alternative preys.

Here, our aim was to estimate densities and numbers of active burrows of white-chinned petrels and grey petrels at Kerguelen Islands, a major breeding locality for both species, taking into account detection probability using the distance sampling method (Buckland *et al.*, 2001) which accounts for a decreasing detectability of objects with increasing distance from the observer. Using these estimates, basic demographic information and the numbers caught in fisheries, we estimated the potential impact of fisheries bycatch on these populations.

Materials and methods

The Kerguelen Islands (48°28′–50°S, 68°28′–70°35′E), Southern Indian Ocean, consist of a main island, Grande Terre, partly covered by an icecap, and secondary islands and islets of which 26 are situated in the Golfe du Morbihan (Fig. 1). The total surface of the archipelago is ~7200 km^2. Vegetation is limited by altitude up to 200–300 m and occurs only along the coast and on the smaller islands. It is dominated by *Azorella selago*, *Acaena magellanica*, Kerguelen cabbage (*Pringlea antiscorbutica*), *Blechnum pennamarina*, *Cotula plumosa* and tussock *Poa cookii*. At higher altitude vegetation is sparse or absent.

Surveys were conducted from November 2004 to March 2005 and from November 2005 to April 2006 on the eastern part of the archipelago at Ronarch', Jeanne d'Arc and Courbet peninsulas and most (70%) islands in Golfe du Morbihan (Fig. 1). Surveys for white-chinned petrels were conducted from November to January, and those for grey petrels in March and April. Because both species nest exclusively in areas covered with peat in which they can dig their burrows, only the vegetated coastal strip up to an altitude of 200 m (above which some sparse vegetation remained but with no suitable soil for petrels to dig their burrows) and the vegetated islands were sampled. A three-stage process was used to estimate the number of active (i.e. occupied or apparently occupied) burrows of each species. First, burrow densities and their variances were estimated in the surveyed area. Second, the proportion of occupied burrows was estimated by play-back and burrow-scoping. Finally the land area corresponding to favourable habitats was calculated for the entire Kerguelen archipelago and multiplied by density to obtain global estimates for the archipelago.

Sampling design

Previous surveys suggest the existence of spatial variation in burrow densities for both species (Weimerskirch, Zotier & Jouventin, 1989). In order to sample the range of densities and habitats represented on the surveyed area and to improve precision, we stratified the eastern part of Kerguelen into 18 geographic sub-entities in which burrow densities were estimated (Fig. 1). We distinguished large sub-entities (i.e. peninsulas), where line-transects were mainly coastal or along large valleys, from islands in the Golfe du Morbihan where line-transects covered the entire islands. On islands, line-transects consisted in parallel lines separated by ~200 m from the end of the previous line, plus coastal lines. On

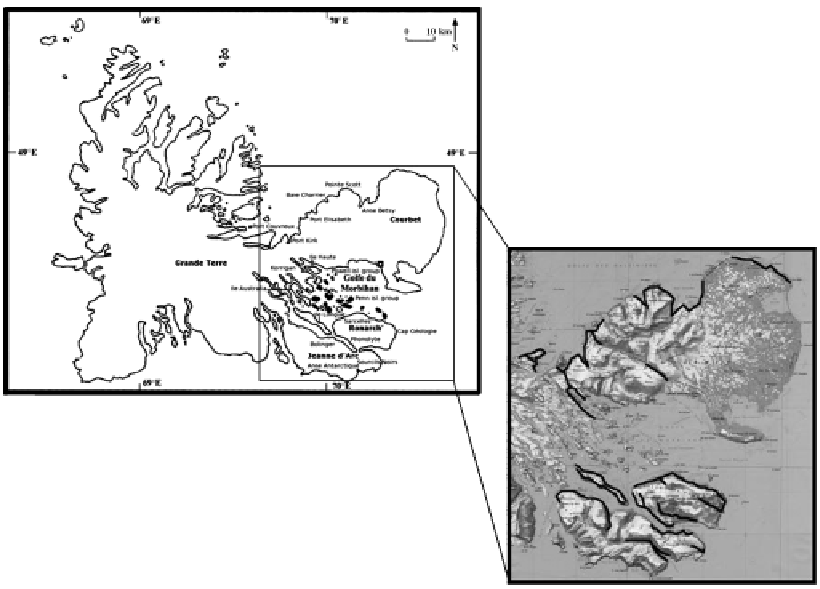

Figure 1 The Kerguelen Islands, Southern Indian Ocean and location of the main geographic entities where line-transects were performed (smaller case). The smaller islands in the Golfe du Morbihan which were surveyed are indicated in black. The black square indicates the position of the Port-aux-Français permanent research station. Also shown are the location of the transects (thick lines on the right panel) on the main island and on the largest island within the Golfe du Morbihan.

Grande Terre line-transects consisted of more or less zigzagging lines separated by ~200 m.

Estimating burrow densities

Burrow densities and their variances were estimated by the line-transects using distance sampling (Buckland *et al.*, 2001). This method uses the distance from the line to the object to correct for visibility bias, and allows estimating the probability of detecting objects and corrected densities. A total of 31 line-transects were distributed across the surveyed area with at least one transect per geographical entity, representing a total length of 566 km. For each transect line, the horizontal perpendicular distance from the transect line to each burrow entrance detected from the line was measured to the nearest metre with a Leica 1200 scan laser rangefinder (Leica, Solms, Germany) or by the number of steps. Because vegetation height at Kerguelen was relatively low compared to other sub-Antarctic island where white-chinned petrels or grey petrels breed (such as South Georgia or Antipodes where petrels nest under fairly dense tussock), burrow entrances were obvious and easy to spot. Lengths measured by the number of steps were calibrated using the laser rangefinder and were ±1 m (range 0–2 m). For burrows situated close to the line the error was close to zero. Burrows either side of the line were recorded. Line-transects were recorded using a handheld GPS unit (Garmin 76CS). To avoid being attracted by areas of high or low densities of burrows during line-transects, observers walked on the heading of distant geographic features (e.g. mountain top). Densities were computed using the software Distance 5.0 (Thomas *et al.*, 2005). For each transect, the truncation level was set following identification of outliers from box plots (outliers were values higher than 1.5 box-lengths from the 75th percentile). Heaping was assessed from histograms, and data were grouped where necessary (Buckland *et al.*, 2001). The probability of burrow detection was estimated with models combining density functions (uniform, half-normal and hazard-rate) with adjustments (cosine, simple, Hermite polynomials) (Fig. 2). The model with the lowest Akaike's information criterion was selected for each site (Burnham & Anderson, 2002). The adequacy of the selected model to the perpendicular distances was assessed by a X^2 goodness-of-fit test on grouped data and by verifying that coefficient of variation of the detection probability did not exceed 20% (Buckland *et al.*, 2001). The four key assumptions of distance sampling are that: (1) objects on the line are detected with certainty ($g(0) = 1$); (2) objects are detected at their initial location; (3) measurements are exact; (4) detections are independent events. To evaluate the first assumption, all transects were covered by pairs of observers walking one behind the other. The first observer was detecting the burrows from the line-transect and was indicating to the second observer all the detected burrows. The second observer was systematically recording whether some burrows present within 1 m from the line were missed by the first observer. No additional burrow was detected by the second observer, so we considered $g(0) = 1$. Since burrows were by

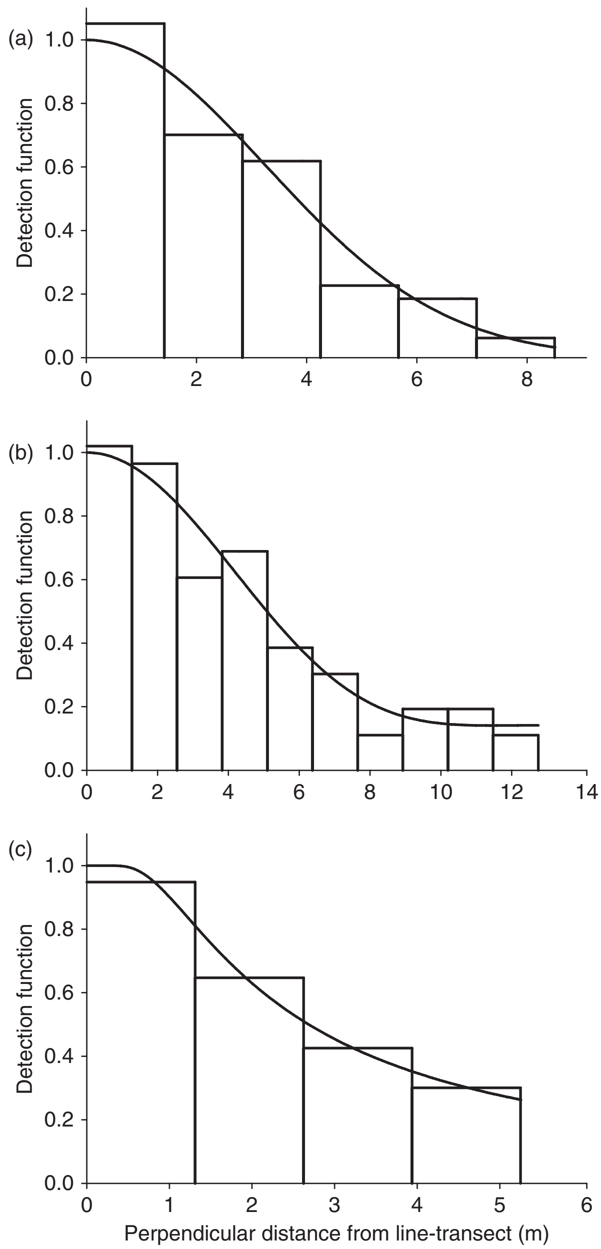

Figure 2 Histograms of the white-chinned petrel *Procellaria aequinoctialis* data for (a) Port Kirk and (b) Pointe Scott geographic sub-entities and (c) of the grey petrel data. Histograms bins have been modified from the original data by program DISTANCE. The best-fitting detection function is also represented in each case: the half-normal and cosine adjustment (a), uniform and cosine adjustment (b), and hazard and Hermite polynomial adjustment (c). Truncation distances are 8.5 m (a), 12.75 m (b) and 5.25 m (c).

definition immobile and assumption two was satisfied. Given that distances were measured at ±1 m and that burrows were found up to several tens of meters from the line-transects we considered assumption three fulfilled. To satisfy the fourth assumption, when distances were measured by number of steps, additional burrows detected while walking from the line to the burrow initially detected, but not detected from the line, were not included in the analysis.

To evaluate the accuracy (but not the precision since it is more dependent on the sample size) of the distance sampling method for estimating burrow densities we did an exhaustive count of burrows of white-chinned petrel on a 1.05 ha restricted area with a high density of burrows. A 206 m line transect sampling was performed in the area and the data were subsequently analysed. Burrows were then systematically searched within the same area by four observers walking in line, each separated by 2 m.

Estimating burrow occupancy

We discriminated the occupant species by looking at the burrow diameter and entrance topography (Zotier, 1990). The white-chinned petrel is the largest burrowing petrel species on Kerguelen and its burrows are of greater diameter than those of other species and are often entered *via* a small pool of water, implying that the risk of misidentifying the occupying species was negligible. Grey petrels dig their burrows in drier ground than used by white-chinned petrels. Grey petrels are smaller that white-chinned petrels, and some burrow entrances initially attributed to grey petrels where occupied by great-winged petrels *Pterodroma macroptera*, also a winter breeder, which often responded to the playback or were detected using a burrow-scope (infrared camera mounted on a flexible wire equipped with a video display system; Sandpiper Technologies Inc, Manteca, CA, USA). Consequently, the estimated number of burrows of grey petrels comprises a proportion of burrows occupied by great-winged petrels. We estimated the proportion of burrows that was occupied by grey petrels using the response to playback and burrow scoping on a sample of 19 line-transects. This proportion (and its standard error) was directly included in the distance sampling analysis as a multiplier (Buckland *et al.*, 2001) to estimate the density of grey petrel burrows.

To assess burrow occupancy we used acoustic playbacks for each species. Because calls are sex-specific in white-chinned petrels (Brooke, 1986; Warham, 1988), calls of both males and females were used. Vocalizations were played 1 mn down all burrow entrances and we recorded whether or not a bird responded. To estimate the proportion of birds present in burrows that would not respond to taped vocalizations (Ratcliffe *et al.*, 1998; Berrow, 2000) we inspected a sample of 50 burrows for white-chinned petrels and 32 burrows for grey petrels using a burrow-scope. The response probability was then calculated as the number of burrows with a response to the playback divided by the number of burrows occupied.

Burrows included in the analyses were those occupied by a bird and those that were empty but which had signs of occupation (i.e. presence of droppings and/or feathers near the entrance, dead vegetation disposed at the entrance by the birds). Collapsed burrows and those for which the entrance was obstructed by vegetation were not included in the analyses. We therefore estimated the number of active burrows for both species in the two seasons in which we did our census and considered these estimates to be a reasonable accurate representation of the number of breeding pairs.

Estimation of area

Numbers of active burrows were calculated by multiplying areas by median densities estimated in the surveyed area for each species. Previous surveys indicate that white-chinned petrels are widespread all over the vegetated areas of Kerguelen (Weimerskirch *et al.*, 1989). For white-chinned petrels, the area of vegetation on Grande Terre and the largest islands was calculated using one Landsat ETM scene taken on 2001/01/11, with a cell size of 28.5 m. Spectral reflectance measurements acquired in the red and near-infrared wavelengths were used to identify areas of vegetation which were calculated through GIS program ESRI (ArcView 3.2 and ArcGis 9). The cloud cover did not permit to calculate the area of vegetation form the Landsat scene for the western coast of Kerguelen. We thus used IGN (National Geographic Institute) maps (scale 1/100 000) to calculate the area of vegetation. Our and previous surveys (Weimerskirch *et al.*, 1989) showed that burrows were situated at elevations from 0 to 200 m, and were absent on the seashore and on flat areas. These areas were excluded from the area of vegetation. We also used historical survey data to exclude some areas (Weimerskirch *et al.*, 1989 and unpubl. data). Since smaller islands in the Golfe du Morbihan were sampled entirely we used the total area of these islands.

Contrary to white-chinned petrels, the breeding distribution of grey petrels is much more restricted (Weimerskirch *et al.*, 1989). Grey petrels are known to breed on the islands of the Golfe du Morbihan, on the eastern end of the Jeanne d'Arc Peninsula and on Joffre, Sainte Lanne Gramont and Port islands, of which only the Golfe du Morbihan was sampled during our survey. Burrows are situated on the coastal areas at elevations from 0 to 200 m, but in dry habitats eventually without vegetation, preventing the use of the vegetated area in the sectors which were not surveyed to estimate the number of burrows as we did for white-chinned petrels. We thus only estimated the number of burrows using density estimates and the surface area of the sites surveyed.

To add the area introduced by slope we calculated an average slope from 25 slope measurements per geographic sub-entity. Slopes were calculated using the isoclines of the IGN maps and the vegetation areas determined from the Landsat scene.

Sensitivity to fisheries

Both petrel species suffer important mortality in fisheries targeting tuna (*Thunnus* spp.), hake (*Merluccius* spp.) and Patagonian toothfish (*Dissosticus eleginoides*). Assessing the importance of such additional sources of mortality is crucial for evaluating their conservation status. We used the demographic invariant method (Niel & Lebreton, 2005) that permits to evaluate the importance of an additional source of mortality using the maximum annual growth rate of the species of concern. Niel & Lebreton (2005) established the following equation to estimate the maximum annual growth rate, $\lambda_{\max}$, for long-lived species:

$$\lambda_{\max} \approx \frac{(s\alpha - s + \alpha + 1) + \sqrt{(s - s\alpha - \alpha - 1)^2 - 4s\alpha^2}}{2\alpha}$$

where s is adult survival and α is age at first breeding. Wade (1998) proposed that any additional source of mortality that approaches a potential excess growth of $0.5N(\lambda_{\max}-1)F_R$ individuals, where N is the number of individuals and F_R is a recovery factor between 0.1 and 1, would be a source of serious concern for the population.

For white-chinned petrels we assumed that age at first breeding and adult survival are identical to those estimated at Crozet (respectively, 6.1 years and 0.895; Barbraud *et al.*, 2008). For grey petrels, a long-term capture–recapture study on Mayes Island (Golfe du Morbihan) permitted to estimate an adult survival of 0.94 and an age at first breeding of 7 years (C. Barbraud & H. Weimerskirch, unpubl. data). Given IUCN status, age and gender bias in mortalities for both species (Bartle, 1990; Delord *et al.*, 2005; Barbraud *et al.*, 2008) we used a value of 0.5 for F_R following Wade (1998). We then assumed that our estimates of the number of active burrows was an upper approximation of the number of breeding pairs, and based on a Leslie matrix model developed for white-chinned petrels at Crozet (Barbraud *et al.*, 2008), we obtained an estimate of the population sizes of grey petrels and white-chinned petrels at Kerguelen. The matrix model included several stages with transition probabilities between stages estimated from demographic parameters. Before the reproductive maturity, individuals move through several annual juvenile stages, then to the pre-breeder stage. The number of juvenile stages ensures that birds cannot breed before the minimum age at first breeding observed for these populations. After the pre-breeding stage individuals enter the adult breeding stage. Finally, an adult non-breeding stage was introduced into the model to take into account the fact that white-chinned petrels and grey petrels occasionally take years off between breeding attempts (Chastel, 1995), during which they remain at sea and are unavailable for detection.

Results

Burrow occupancy

For white-chinned petrels, a total of 3547 burrows were detected of which 60.1% were occupied, 34.3% had signs of occupation, and 5.6% were collapsed. For grey petrels, 474 burrows were detected of which 8.5% were occupied, 89.2% had signs of occupation and 2.3% were collapsed. The difference in the proportions of burrows occupied and with signs of occupation between both species reflects the fact that grey petrel burrows were sampled at the beginning of the breeding season (start of laying), whereas white-chinned petrels were sampled during the breeding season (incubation and early chick rearing) due to differences in breeding phenology. For both species the response rate to the playback was 1. No other species was found in burrows attributed to white-chinned petrels. In burrows attributed to grey petrels, the proportion of burrows occupied by grey petrels was estimated at 0.46 (SE = 0.085), the rest being occupied by great-winged petrels.

Densities and population estimates

Burrow densities were estimated using active burrows (i.e. those occupied and those having signs of occupation), which represented 94.4 and 97.7% of the detected burrows for white-chined and grey petrels, respectively. Burrow detection probabilities ($\pm$SE) were lower than one for both species, varying between 0.19 ± 0.03 and 0.58 ± 0.06 (Table 1).

In the area chosen to evaluate the accuracy of the method, a total of 28 burrows were detected. The lowest AIC model (half-normal) showed a good fit ($P = 0.531$) and yielded a density of 114.41 burrows ha^{-1}. The total area, taking into account the area added by slope (40°), was 1.37 ha, which yielded an estimate 156 burrows (95% CI: 81–301). The total number of burrows found during the exhaustive search was 157, indicating that the method was accurate.

White-chinned petrel burrows were found in all line-transects. For a few line-transects the number of burrows found was too low for analysis using Distance, and these were grouped together to obtain a sufficient sample size. For white-chinned petrels, the lowest AIC models showed good fit (Table 1; $P = 0.063$–0.902, median P value = 0.372). Active burrow densities varied from 1.89 burrows ha^{-1} (95% CI: 1.37–2.64) to 25.77 burrows ha^{-1} (95% CI: 20.94–21.73). The median active burrow density was 7.89 burrows ha^{-1} (median of lower 95% CI densities: 6.28; median of higher 95% CI densities: 9.91). The estimated vegetated area favourable for white-chinned petrels in the surveyed area was 12 539.4554 ha, adjusted for an average slope of 23.35°. For each geographic sub-entity, active burrow density was multiplied by the vegetated area to estimate the number of occupied burrows in the surveyed area. There were 74 000 active burrows of white-chinned petrels (95% CI: 58 000–95 000) in the surveyed part of Kerguelen. Using the vegetated area of the rest of the Kerguelen archipelago (20 369.23 ha) and the median active burrow density calculated in the surveyed area, we estimated there were 234 000 (95% CI: 186 000–297 000) active burrows.

Grey petrel burrows were only found on line-transects in the islands of the Golfe du Morbihan. Owing to low numbers of burrows detected for some line-transects, we grouped data from all line-transects. The lowest AIC models showed good fit ($P = 0.350$–0.916). Active burrow density was 2.78 burrows ha^{-1} (95% CI: 1.61–4.81). Using the surface area adjusted for slope of the islands sampled during the surveyed and those for which grey petrels are known to breed (1222 ha), there were an estimated 3400 (95% CI:

Table 1 Selected best models used for estimating burrow densities for each geographic entity for white-chinned petrels *Procellaria aequinoctialis* and for grey petrels *Procellaria cinerea* at Kerguelen

Entity	Model	Adjustment	AIC	GOF	$\hat{D}$	SE $(\hat{D})$	$\hat{p}$	SE $(\hat{p})$
Port Elisabeth	Hazard	Cosinus	729.2	0.739	12.62	4.48	0.54	0.07
Port Kirk	Half-normal	Cosinus	421.2	0.557	11.71	6.70	0.47	0.03
Anse Betsy	Half-normal	Cosinus	140.1	0.554	15.34	13.92	0.31	0.04
Pointe Scott	Uniform	Cosinus	689.8	0.690	25.77	5.23	0.46	0.03
Baie Charrier	Hazard	Cosinus	441.0	0.512	16.73	3.33	0.32	0.04
Port Couvreux	Half-normal	Cosinus	209.7	0.077	1.37	0.67	0.19	0.02
Korrigan	Half-normal	Cosinus	104.3	0.902	3.51	1.92	0.33	0.10
Anse Antarctique	Hazard	Cosinus	429.0	0.310	1.78	0.54	0.35	0.05
Sourcils Noirs	Half-normal	Cosinus	334.3	0.347	18.58	11.44	0.34	0.03
Bolinger	Half-normal	Cosinus	198.6	0.426	2.18	0.70	0.33	0.04
Cap Géologie	Half-normal	Cosinus	924.6	0.160	10.72	2.48	0.30	0.02
Sarcelles	Half-normal	Cosinus	563.1	0.161	2.88	1.42	0.31	0.02
Phonolyte	Uniform	Cosinus	538.8	0.063	1.95	0.32	0.36	0.03
Ile Haute	Hazard	Simple	621.6	0.396	7.89	1.61	0.41	0.04
Ile Longue	Half-normal	Cosinus	712.6	0.426	3.92	0.92	0.38	0.03
Ile Australia	Hazard	Simple	271.6	0.243	1.90	0.85	0.43	0.06
Powell isl. group	Hazard	Cosinus	1332.8	0.188	10.63	1.86	0.39	0.03
Penn isl. group	Half-normal	Simple	594.7	0.217	4.86	0.96	0.22	0.01
Grey petrel	Hazard	All	1065.5	0.916	2.78	0.79	0.58	0.06

AIC, Akaïke information criterion; GOF, goodness-of-fit *P*-value; $\hat{D}$, density (burrows/ha); SE, standard error; $\hat{p}$, detection probability.

1900–5600) active burrows of grey petrels in the surveyed area.

Sensitivity to fisheries

For white-chinned petrels and grey petrels we estimated $\lambda_{max} = 1.094$ and $\lambda_{max} = 1.068$, respectively. Based on the estimated number of breeding pairs and on a Leslie matrix model, the population size of grey petrels and white-chinned petrels at Kerguelen were respectively close to 19 000 (95% CI: 10 600–31 300) and 1 336 000 individuals (95% CI: 1 062 000–1 696 000). Then, any additional source of mortality that, respectively, approaches 300 individuals (180–530 individuals) and 31 000 individuals (25 000–40 000 individuals) for grey petrels and white-chinned petrels would likely result in a decline of the populations.

Discussion

Our estimates of the number of active burrows do not necessarily represent estimates of the number of breeding pairs. The timing of the surveys corresponded to the incubation and early chick rearing periods for white-chinned petrels, and to the laying period for grey petrels (Brooke, 2004). It is therefore likely that we underestimated the number of active burrows, since a proportion of burrows of grey petrels were eventually frequented and received an egg after we had completed our survey, and a proportion of burrows of white-chinned petrels might have failed before our survey and were recorded as unoccupied. However, we think these proportions were small, since most grey petrel eggs are laid by mid-April (Zotier, 1990), and burrows with failed white-chinned had probably remaining signs of occupation. Second, only a proportion of active burrows may receive an egg (i.e. not all burrows with signs of occupation may have receive an egg). This proportion was estimated at ~63% for white-chinned petrels at Crozet in 2004 (Barbraud *et al.*, 2008), but it may be species, year and site specific. All white-chinned petrels do not breed every year with, respectively, 91 and 88% of successful and unsuccessful birds breeding the following year at Crozet (Chastel, 1995). Therefore the estimated number of active burrows of white-chinned petrels probably represents an upper limit for the number of breeding pairs. For grey petrels, we could only estimate the number of active burrows in the Golfe du Morbihan. A very small (10's) number of pairs breed at the eastern end of the Jeanne d'Arc peninsula in inaccessible areas. Numbers are unknown at Joffre peninsula, Sainte Lanne Gramont and Port islands, but historical visits suggest relatively low densities compared with those observed on the islands from the Golfe du Morbihan. Furthermore, on the mainland, such as Joffre Peninsula, it is likely that grey petrels have now disappeared with the extension of cats (Say *et al.*, 2002). In addition, it is very unlikely that high numbers of grey petrels breed in the western part of Kerguelen which is much wetter than the eastern part. At Kerguelen, about 93 and 81% of successful and unsuccessful grey petrels bred the following year (Chastel, 1995), and 86% of burrows were occupied by breeders at Antipodes in 2001 (Bell, 2002). Therefore as for white-chinned petrels, the estimated number of active burrows of grey petrels probably represents an upper limit for the number of breeding pairs.

The only previous estimates of breeding pairs at Kerguelen were of 100 000 to 300 000 for white-chinned petrels and of 5000 to 10 000 for grey petrels (Weimerskirch *et al.*, 1989).

These figures were rough estimates and did not take into account detectability or habitat characteristics. Results from the current study suggest relatively similar estimates, but the different methodologies used do not permit to draw inferences on population trends. At a global scale, Kerguelen is a key breeding site for white-chinned petrels, which hosts most of the breeding population of the Southern Indian Ocean (Brooke, 2004; Barbraud *et al.*, 2008), although estimates on islands from the south Atlantic and south Pacific need to be re-assessed. A recent survey at South Georgia suggests that previous estimates (~2 million breeding pairs; Prince & Croxall, 1983) were probably too high, but that South Georgia holds 0.9 million breeding pairs (Martin *et al.* 2009). Kerguelen also probably represents a key breeding site for grey petrels as the largest breeding populations are found at Gough Island (10 000–25 000 breeding pairs; Brooke, 2004) and at Antipodes Islands (~53 000 breeding pairs; Bell, 2002), although again estimates from the other breeding localities need to be re-assessed.

We found that any additional source of mortality that, respectively, approaches 300 and 31 000 individuals for grey petrels and white-chinned petrels would likely result in a decline of the populations. Therefore, the strict minimum of 755 grey petrels killed annually in the legal and illegal Patagonian fisheries operating around Kerguelen since 1996 (Delord *et al.*, 2005; CCAMLR reports http://www.ccamlr.org/; Terres Australes et Antarctiques Françaises, unpubl. data) is already above this maximum additional mortality. For white-chinned petrels the minimum of 12 174 individuals killed annually in the same fishery (Delord *et al.*, 2005; CCAMLR reports http://www.ccamlr.org/; Terres Australes et Antarctiques Françaises, unpubl. data) already represents 28.2% of the maximum additional mortality, but unknown numbers are caught in hake and tuna fisheries. However, the number of white-chinned petrels killed was <1500 individuals in the French EEZ for the 2007 fishing season (SC-CAMLR-XXVI, 2007), due to the implementation of mitigation measures, and steps are being taken to further reduce the number being killed in this local fishery. More than 31 900 white-chinned petrels are estimated being killed by demersal longline fleets fishing in the Benguela Current marine ecosystem each year (Petersen *et al.*, 2007), where white-chinned petrels breeding at Kerguelen spend the none breeding season (H. Weimerskirch, unpubl. data), although the Benguela ecosystem also hosts white-chinned petrels breeding at Crozet (Weimerskirch *et al.*, 1999). Additionally, a large proportion of unoccupied burrows classified as active was used in the analyses, which constitutes a considerable source of uncertainty, particularly for grey petrels. If many of these burrows remain unoccupied in any season, a possibility that we can not entirely exclude, then the proportional damage caused by fisheries is even higher. Clearly, fishery-related losses for the Kerguelen populations of grey petrels and white-chinned petrels can be considered a serious threat for the species at least at the regional scale of the Southern Indian Ocean.

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