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ORIGINAL PAPER

Multivariate effects on seabird bycatch in the legal Patagonian toothfish longline fishery around Crozet and Kerguelen Islands

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Abstract The effects of temporal, spatial, environmental and operational effects on seabird incidental mortality in the legal Patagonian toothfish longline fishery operating, between 2003 and 2006, in French exclusive economic zones of Crozet and Kerguelen Islands were analysed. During the study period, the mean bycatch rate varied from 0.05 to 0.12 birds per 1,000 hooks. Two species were concerned by incidental mortality: white-chinned petrels (88%) and grey petrels (11.5%). Males of white-chinned petrel seemed more at a risk than females. Logbooks data tended to underreport mortality when compared with dedicated fishery observers. The results indicate that temporal (season or phenology) and spatial (area) factors reflecting mortality risk for seabirds played the most significant role in the incidental mortality of the two species. Operational (integrated weight mainline, number of scaring lines and number of hooks hauled) and environmental factors (wind/vessel angle, moon brightness) were also influential, although less significantly, in increasing this mortality risk. Our two steps analyses by separately modelling the probability of presence and the abundance given presence suggest that the decrease in seabird bycatch over the period was mainly due to an important decrease in probability (occurrence) of mortality.

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Introduction

Fishing operations attract a range of marine predator species. Incidental mortality of seabirds on fishing vessels is well documented, and there is mounting evidence that longline fishing is a major cause of observed decrease of albatross and petrel populations (Barbraud et al. 2008; Brothers 1991; Nel et al. 2003; Robertson and Gales 1998; Sullivan et al. 2006; Tuck et al. 2001; Weimerskirch et al. 1997). Birds are drowned after being hooked when attempting to take baits. Encouragingly, changes in fishing practices and technological innovations have spurred reductions of seabird bycatch (Bull 2007; Brothers et al. 1999a; Melvin and Parrish 2008). The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which is the Regional Fisheries Management Organization—RFMO—for the Southern Ocean, has adopted those mitigation measures. CCAMLR efforts to reduce bycatch and collect comprehensive data on wildlife interactions with fisheries (Small 2005) are unprecedented. Effective mitigation measures include keeping birds away from baited hooks (e.g. bird-scaring lines), reducing the time the hook is available to the birds (e.g. line weighting or line setting chutes), avoiding peak periods of bird foraging (e.g. night setting) or making vessels or bait less attractive to the birds (offal management). Those efforts have led to an important reduction in longline seabird mortality, from tens of thousands individuals in the late 1990s to hundreds in the late 2000s.

Although seabird mortality is near zero for CCAMLR fisheries, it is still high in the French exclusive economic zones (EEZs) fisheries (Delord et al. 2005; SC-CAMLR 2006). Following the implementation of a subset of the mitigation measures suggested by CCAMLR by the French Southern Territories, there were important reductions in incidental seabird mortality from nearly 12,000 individuals per year in the early 2000s to approximately 1,000 actually (SC-CAMLR 2008). Seasonal differences in the fishing patterns between areas may account for the differences between the French EEZs and other areas. No longline fishing was conducted outside the EEZs during the summer period, which is at a high risk for seabird captures, especially for white-chinned petrels (*Procellaria aequinoctialis)*. Furthermore, French EEZs host several populations of grey petrels (*Procellaria cinerea*), a winter breeding species (Barbraud et al. 2009). White-chinned petrels and grey petrels remain the two species caught incidentally, while bycatch of other species no longer occurs. Their wide foraging range, diet and diving abilities make them amongst the most difficult species to deter from baited hooks (Murray et al. 1993; Huin 1994; Ridoux 1994; Catard et al. 2000; Nel et al. 2002; Favero et al. 2003; Delord et al. 2005; Phillips et al. 2006; Robertson et al. 2006).

The CCAMLR, the Agreement on the Conservation of Albatross and Petrels (ACAP) and the Southern Indian Ocean Fisheries Agreement (SIOFA) recommendations on seabird bycatch all require a better identification of factors affecting seabird incidental mortality on spatial and temporal scales as fine as possible. Here, we examine the relative influence of various operational, spatial, temporal and environmental factors on white-chinned petrels and grey petrels incidental mortality caused by the legal Patagonian toothfish (*Dissostichus eleginoides*) longline fishery operating in the French EEZs in the Southern Indian Ocean. We test whether the implementation of new mitigation measures had a significant impact on mortality. Fishing vessels operate in the French EEZs around the Crozet (CCAMLR-Subarea 58.6) and Kerguelen (CCAMLR Division 58.5.1) archipelagos (Fig. 1). After a high-mortality period in the late 1990s early 2000s (Cherel et al. 1996; Delord et al. 2005; Weimerskirch et al. 2000), we studied the period 2003–2006 when new mitigation measures were implemented.

Materials and methods

Data collection

The fishing season extends from 1 September to 31 August of the following year. The automatic hook-baiting system (Mustad® and BFG®) remains to be the only type of longliner operating in the area during the 2003–2006 period. The vessels ($n = 8$) set longlines with several thousands of hooks (mean 8,945 ± 161 hooks (375–32,400; $n = 10{,}426$)) and can set 1–9 longlines during one night (only night setting is authorised). All the fishing vessels were autoliners using side setting, used white coloured lines, had lines weighted either through use of integrated weight lines (IW: 50 g/m leaded cord, or 160 g/m total weight) or through adding weights to lines manually (non-IW: 5 kg every 50 m: 100 g/m) and both combined, and the fisheries wastes were not discharged during setting (stopping at least 30 min before the start of setting) (Official Journal of the French Southern Territories *TAAF*). Offal discharge took place continuously during the hauling process, depending on the catch targeted species and fish bycatch and was attractive and accessible to seabirds.

During the three fishing seasons 2003/2004, 2004/2005 and 2005/2006, a complete coverage by observers ($n = 20$) was undergone on each vessel—an observer is on each vessel all of the time that it is fishing. The observers were instructed to collect statistical and biological data on fishing operations and to quantify the incidental mortality of seabirds by the observation of a percentage of hooks hauled.

During the study period, the collecting protocol of incidental mortality data was modified compared with the previous years to harmonise data collection with what is applied in other CCAMLR areas. The incidental mortality originally (during 2003/2004 and 2004/2005) reported corresponded to the captain's logbook −100% estimated mortality. During 2003/2004, the observation effort was not recorded and estimated to be <10–15% of hooks hauled observed (Delord et al. 2005). Thereafter, the observers increased their observation effort to 25% of the hooks hauled corresponding to 25% observed mortality. This collecting protocol was applied on part of the settings during 2004/2005 and finally on all the settings thereafter (since 2005/2006). Thus, 2004/2005 represented a turning point with the coexistence of the two different collecting protocols (captain's logbook and fishery observers). Thus, we estimated the relationship between incidental mortality rates reported by captains and by observers during 2004/2005.

All the birds incidentally caught during observation effort were taken onboard during hauling of the mainline and were identified at the species level.

The total estimated mortality was calculated from the observed mortality corrected by the rate of hook loss between line setting and line hauling ratio number of hooks set/number of hooks hauled.

The observers determined the sex of individuals incidentally killed from a sample of white-chinned petrels ($n = 515$) caught by four vessels, on 71 settings during 2003/2004 and on 15 settings during 2004/2005. No identification of sex was performed for grey petrels.

The data collected included fishing and operational data as well as spatial and temporal variables. Fishing and operational data incorporated the vessel, duration of the

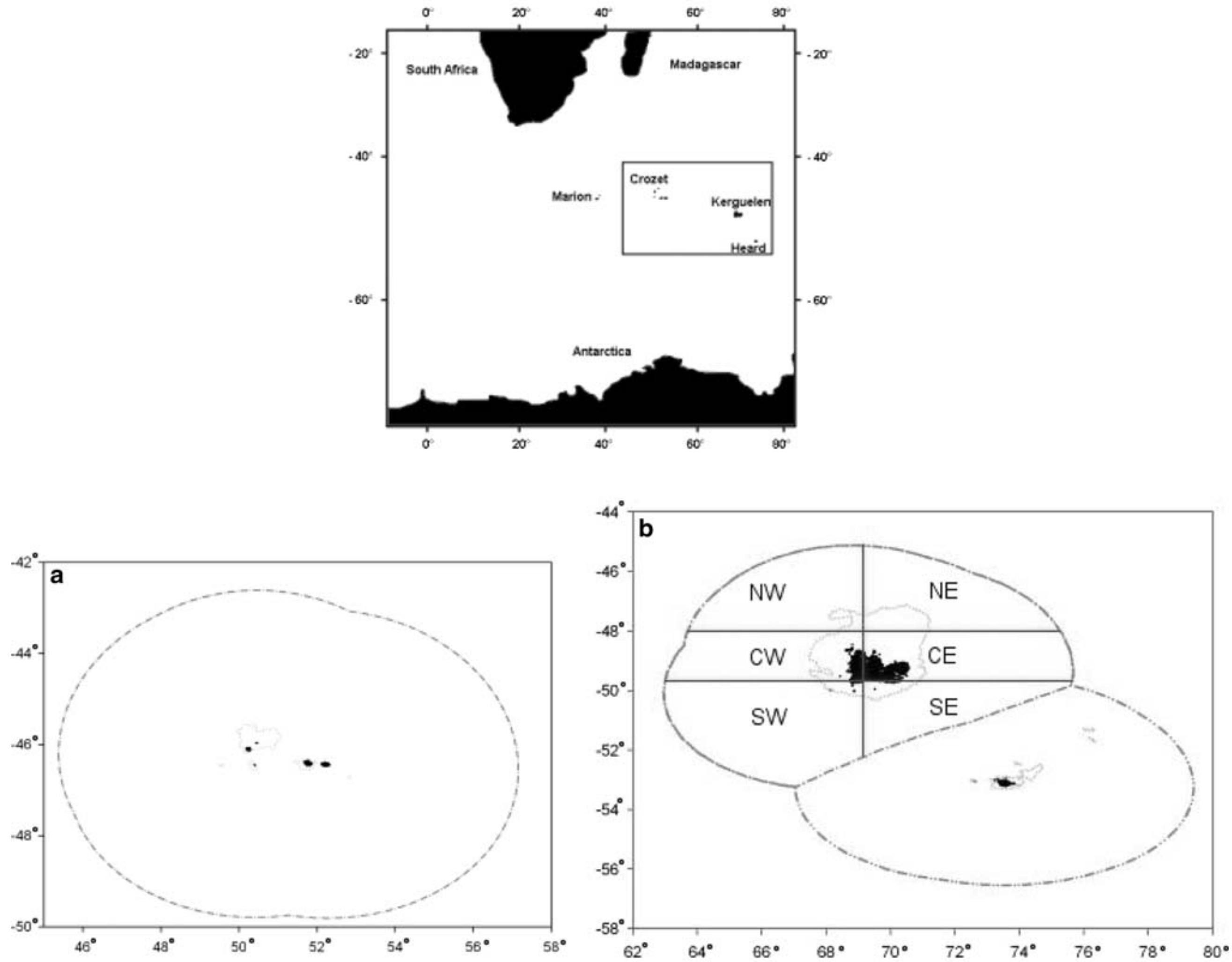

Fig. 1 Map of the French EEZs around **a** Crozet archipelago (CCAMLR-Subarea 58.6) and **b** Kerguelen Island (CCAMLR Division 58.5.1) divided into six zones: northeast (*NE*), centre-east (*CE*), southeast (*SE*), northwest (*NW*), centre-west (*CW*) and southwest (*SW*)

trip, number of hooks set and hauled, vessel speed and course, swell direction, moon intensity, cloud cover, wind speed and direction, sea state, bathymetry, set and haul time, bait type, estimated quantity of discarded offal (calculated using the difference landed and green weight for each species), two mitigation measures (line-weighting mode, number of streamer line) and fish caught (Patagonian toothfish) per set. The bird-scaring system consisted of streamer lines (1–7) attached at the stern. Detailed information on the design of the streamer line (material, attachment details …) and aerial coverage of the system were not reported.

Statistical analyses: modelling

Seabird incidental mortality data typically exhibit two features: a substantial proportion of the values are zero, and the remainder has a skewed distribution. During the study period, only two species were concerned by incidental mortality: white-chinned petrels and grey petrels. Thus, we conducted the analyses in two steps (see Fletcher et al. 2005 for more details) for each species. We first created two datasets: one indicating whether there is (1) or not (0) incidental mortality on the setting, the other showing the log-transformed number caught for those settings where petrels were accidentally killed. Thereafter, these two data sets are referred to the “presence data” and the “log-abundance data”, respectively. For the log-abundance data, to take into account, the change in the mortality recording protocol during the study period, we performed two separate analyses: one including the first 2 years (2003/2004, 2004/2005) using bycatch reported by captains, and one including the last 2 years (2004/2005, 2005/2006) using bycatch reported by observers.

We then modelled both the presence data and the log-abundance data as a function of explanatory variables. In

Table 1 Variables used in the analyses of seabird bycatch during 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Factors	
Environmental	
Beaufort	Sea state Beaufort scale (0–12)
Moon brightness	Integrating moon phase, nebulosity and position of the moon above the horizon line
Bathymetry	
Wind/vessel angle	Angle between vessel course and wind direction
Spatial	
Area	Crozet Kerguelen: northeast, centre-east, southeast, northwest, centre-west, south-west
Temporal	
Year	Fishing seasons 2003/2004, 2004/2005 and 2005/2006 (from 1 September to 31 August)
Season	Summer, winter
Phenology	Pre-laying, incubation, brooding or non-breeding
Operational	
Weighted regime	Calculated in g/m
Bait	Type of bait used
Setting speed	Miles/h
Set number	Order in which longlines are set (e.g. n°1 is set first…)
Scaring line	Number of scaring line
Number of hooks hauled	Number of hooks per set
Integrated weight	Integrated, non-integrated or combined
Quantity of offal	kg

addition to parameters collected by the observers, we used data on the phenology of each species. We distinguished four periods for white-chinned petrels, pre-laying (exodus of breeding petrels preceding egg laying), incubation, brooding and non-breeding, and two periods, breeding and non-breeding, for grey petrels due to a smaller sample size. White-chinned petrels breed during the austral summer (pre-laying in September and October, incubation in November and December, brooding from January to March and non-breeding from April to August) while grey petrels breed during winter from February (pre-laying) to October (brooding).

To examine the relationships between seabird bycatch and environmental, spatial, temporal and operational factors (see Table 1), we used generalised linear mixed models to account for autocorrelation of the data. Indeed, some factors were linked from one day to the next (i.e. sea state), while others were intrinsically linked to vessels throughout the entire trip (i.e. observer, fishing gear). As a result, "vessel" was considered as a random factor in the mixed models and all other factors as fixed effects to explain variation in the incidental mortality per line. Because mortality is observed on the hooks hauled, we used the covariate number of hooks hauled instead of number of hooks set. Mortality on the number of hooks set is unknown because the mortality on the rate of hook loss between line setting and line hauling is unknown. Therefore, we did not consider mortality that occurred during the hauling process.

We used the GLIMMIX and MIXED procedures for analysing, respectively, presence and log-abundance data SAS Institute (1998–2001).

The modelling approach used was developed by building general models that included all individual factors and interactions. Interactions to be tested were selected by a priori graphical exploration of the data and the results from previous studies. All relevant parameters were tested for each analysis (except vessel and observer which were redundant). Type-3 tests of fixed effects were used to infer the statistical significance of factors and interactions on the incidental mortality. We used the ratio deviance of the model/degrees of freedom (DF) as a goodness-of-fit test to verify the fit of the data to each model tested. The best fit for the analysis of presence data was obtained with a binomial distribution and a logit link function; whereas for the analysis of log-abundance data, we used a Gaussian distribution and a log-link function. Nonetheless, there was still overdispersion in the data for each analysis (deviance/DF >1). Thus, we used an overdispersion coefficient calculated as the ratio deviance/DF (*P* scale adjustment). We considered a significance level of 0.05. All mean values are presented ±1 SE.

Table 2 Summary of observed seabird bycatch during 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Collecting protocol of incidental mortality data[a]	2003/2004	2004/2005		2005/2006
	Logbook	Logbook	Fishery observers	Fishery observers
Total observed mortality (number of birds)	3,241	2,038	1,111	604
White-chinned petrel	2,965	1,822	1,007	506
Grey petrel	266	216	104	94
Number of hooks set	33,494,913	31,700,790	31,700,790	32,297,395
Rate of incidental mortality [mean ± SE number of birds/1,000 hooks (min–max)]	0.10 ± 0.36 (0–5.56)	0.05 ± 0.20 (0–4)	0.12 ± 0.57 (0–8.94)	0.06 ± 0.31 (0–5.88)
Total estimated mortality (number of birds)	3,277	4,755	4,828	2,436

[a] Logbook corresponds to captain's logbook, reporting 100% estimated mortality, and fishery observers corresponds to a sampling coverage of 25% of hooks hauled

Results

Incidental mortality

During the study period, 5,883 seabirds were observed incidentally killed by legal longliners in the French EEZs of Crozet (58.6) and Kerguelen (58.5.1) (Table 2). We estimated that from 7,766 to 10,541 seabirds were incidentally killed during this period. White-chinned petrels represented 88.2% (±2.3) of birds caught, of which 72.6% were males (binomial test for a bias in sex ratio: $P < 0.05$), the rest being grey petrels (mean 11.5% ± 2.2). During summer (September–April) white-chinned petrels represented 98.1% ± 1.3 of incidental mortality, whereas during winter (May–August) grey petrels represented 96.4% ± 1.0 of incidental mortality. No albatross or other petrel species was observed killed incidentally during the study period.

The fishing effort (total number of hooks sets/year) at Kerguelen was 10–17 times higher than the one observed at Crozet (respectively, $2.5 \times 10^6 \pm 1.4 \times 10^6$ and $0.2 \times 10^6 \pm 0.08 \times 10^6$ hooks per year).

Collecting protocol of incidental mortality data

We estimated the relationship between incidental mortality reported by captains and by observers during 2004/2005. The best fit was obtained with the quadratic function ($y = 0.1255 + 0.4134 \times x\text{-}0.0013 \times x^2$) where x is the incidental mortality reported by fishery observers and y is the captain's logbook incidental mortality ($r^2 = 0.814$; $P < 0.001$; $n = 3277$).

Multivariate effects

White-chinned petrel

The probability of incidental mortality of white-chinned petrels and the numbers caught varied significantly according to several factors (Tables 3, 4). Some factors had a significant effect on the probability of being caught (phenology, weighted regime and setting speed) while others affected only the numbers killed (quantity of offal).

The probability of mortality was higher during the breeding period (pre-laying, incubation and brooding periods) than during the non-breeding period. However, phenology did not explain significant variations in numbers caught (Table 4).

The probability of incidental mortality and the numbers killed varied geographically. The lowest mortality was observed at Crozet compared with Kerguelen irrespective of the zone considered. The highest mortality was observed in northeast, northwest and centre-east of Kerguelen.

Table 3 Fixed-effect- and random-effect (vessel) parameters of generalised linear mixed model (GLMM) of the variation of incidental mortality (occurrence) of white-chinned petrels in 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Factor	Presence data			
	Num DF	Den DF	*F* value	*P* value
Weighted regime	1	7,782	12.86	<0.01
Bait	2	7,782	13.92	<0.0001
Setting speed	1	7,782	6.98	<0.01
Wind/vessel angle	5	7,782	7.07	<0.0001
Area	6	7,782	13.40	<0.0001
Set number	1	7,782	5.64	<0.05
Integrated weight	2	7,782	6.88	<0.01
Phenology[a]	3	7,782	7.57	<0.0001
Scaring line	1	7,782	18.20	<0.0001
Number of hooks hauled	1	7,782	35.52	<0.0001
Moon brightness × phenology[a]	3	7,782	5.53	<0.01
Weighted regime × bait	2	7,782	12.97	<0.0001

[a] Pre-laying: September–October, incubation: November–December, brooding: January–March, non-breeding: April–August

DF degree of freedom, *Num DF* numerator degrees of freedom, *Den DF* denominator degrees of freedom

Table 4 Fixed-effect- and random-effect (vessel) parameters of generalised linear mixed model (GLMM) of the variation of incidental mortality (abundance) of white-chinned petrels in 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Factor	Log abundance 2003/2004 and 2004/2005				Log abundance 2004/2005 and 2005/2006			
	Num DF	Den DF	*F* value	*P* value	Num DF	Den DF	*F* value	*P* value
Year	1	965	11.05	<0.01	1	567	2.77	n.s.
Quantity of offal	1	965	6.94	<0.01	1	567	4.11	<0.05
Weighted regime	1	965	9.36	<0.01	1	567	0.00	n.s.
Bait	2	965	5.84	<0.01	2	567	4.04	<0.05
Area	6	965	5.39	<0.0001	6	567	3.47	<0.01
Set number	1	965	7.67	<0.01	1	567	5.45	<0.05
Number of hooks hauled	1	965	17.96	<0.01	1	567	5.15	<0.05
Moon brightness × phenology[a]	2	965	8.74	<0.01	2	567	0.87	n.s.
Weighted regime × bait	2	965	3.95	<0.05	2	567	3.25	<0.05
Weighted regime × scaring line	1	965	9.50	<0.01	1	567	0.03	n.s.
Scaring line × phenology	2	965	6.72	<0.01	2	567	0.29	n.s.
Quantity of offal × phenology	2	965	2.88	n.s. (0.056)	2	567	1.70	n.s.

[a] Pre-laying: September–October, incubation: November–December, brooding: January–March, non-breeding: April–August

n.s. not significant, *DF* degree of freedom, *Num DF* numerator degrees of freedom, *Den DF* denominator degrees of freedom

Table 5 Fixed-effect- and random-effect (vessel) parameters of generalised linear mixed model (GLMM) of the variation of incidental mortality (occurrence) of grey petrels in 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Factor	Presence data			
	Num DF	Den DF	*F* value	*P* value
Beaufort	1	7,793	14.25	<0.01
Wind/vessel angle	5	7,793	4.89	<0.01
Area	6	7,793	12.72	<0.0001
Set number	1	7,793	22.39	<0.0001
Integrated weight	2	7,793	11.08	<0.0001
Season[a]	1	7,793	33.73	<0.0001
Scaring line	1	7,793	7.08	<0.01
Moon brightness × season	1	7,793	4.04	<0.05
Weighted regime × scaring line	1	7,793	4.77	<0.05
Scaring line × integrated weight	2	7,793	3.64	<0.05

[a] Winter: November–February, summer: March–October

DF degree of freedom, *Num DF* numerator degrees of freedom, *Den DF* denominator degrees of freedom

There was clear evidence that increasing numbers of hooks hauled was associated with an increase in both probability (Table 3) of incidental mortality of white-chinned petrels and numbers caught (Table 4).

The use of combined longlines was related to higher probability of mortality compared with IW or even to non-IW longlines. The numbers caught appeared not to be affected by this factor irrespective of the period (Table 4).

The number of scaring lines used astern the vessels during setting affected significantly the probability of mortality. The higher the number of scaring lines used, the lower was the probability of mortality.

Grey petrel

The probability of incidental mortality and the numbers of grey petrels killed varied significantly according to one common factor: wind/vessel angle (Tables 5, 6). Some factors had a significant effect on the probability of incidental mortality (season, area, set number, weighted regime, number of scaring lines and Beaufort) while others affected only the numbers caught (Table 6). The factors affecting the numbers caught varied between years. Weighting regime alone had no significant effect on the probability of incidental mortality, but the interactions scaring line × weighting regime as well as moon brightness × season had a significant effect (Table 5).

When compared with white-chinned petrels, incidental mortality of grey petrels occurred less frequently (only for 3% of the settings during the study period).

As for white-chinned petrels, the probability of mortality of grey petrels varied geographically. The lower mortality was observed at Crozet compared with Kerguelen, irrespective of the zone considered, and the highest mortality was

Table 6 Fixed-effect- and random-effect (vessel) parameters of generalised linear mixed model (GLMM) of the variation of incidental mortality (abundance) of grey petrels in 2003/2004, 2004/2005 and 2005/2006 in French EEZs

Factor	Log abundance 2003/2004 and 2004/2005				Log abundance 2004/2005 and 2005/2006			
	Num DF	Den DF	*F* value	*P* value	Num DF	Den DF	*F* value	*P* value
Year	1	178	1.49	n.s.	1	140	29.83	<0.0001
Quantity of offal	1	178	0.05	n.s.	1	140	4.63	<0.05
Weighted regime	1	178	0.33	n.s.	1	140	4.82	<0.05
Bait	1	178	0.12	n.s.	1	140	4.40	<0.05
Setting speed	1	178	1.15	n.s.	1	140	9.42	<0.05
Wind/vessel angle	5	178	2.35	<0.05	5	140	3.04	<0.05
Area	6	178	3.86	<0.05	6	140	0.70	n.s.
Set number	1	178	4.63	<0.05	1	140	0.96	n.s.
Bathymetry	1	178	0.43	n.s.	1	140	5.05	<0.05
Weighted regime × bait	1	178	0.05	n.s.	1	140	4.76	<0.05
Quantity of offal × season[a]	1	178	0.02	n.s.	1	140	3.25	n.s. (0.074)

[a] Winter: November–February, summer: March–October

n.s. not significant, *DF* degree of freedom, *Num DF* numerator degrees of freedom, *Den DF* denominator degrees of freedom

observed in centre-east, northwest and southwest of Kerguelen. The probability of mortality was higher during than outside the breeding period, and the season did not explain significant variations in numbers caught (Table 6).

The use of combined longlines clearly increased the probability of mortality of grey petrels compared with other longlines. Furthermore, the number of scaring lines used astern the vessel during setting affected significantly differently the probability of mortality depending on whether IW lines were used or not (and combined). An increasing number of scaring lines were accompanied by a decrease in mortality probability for non-IW or combined longlines, while it did not appear to affect mortality for IW ones.

Poor weather conditions—corresponding to a higher Beaufort index—clearly increased the mortality probability. Likewise, broadside or astern wind/vessel angle increased the mortality.

Discussion

Obtaining accurate estimates of bycatch require the use of unbiased methods for collecting incidental mortality data. The simultaneous collection of bycatch data by dedicated fishery observers and captains (logbook data) permitted us to evaluate the discrepancy between both the methods. Logbooks tended to underreport mortality by approximately 40%, and, consequently, capture rates were underestimated. This was suggested for many fisheries with bycatch concerns (Gales et al. 1998; Weimerskirch et al. 2000; Bugoni et al. 2008). This reinforces the need of dedicated onboard observers for collecting accurate incidental mortality data, and for the implementation of independent observer programmes in many fisheries.

A minimum of 7,766 (max 10,541) seabirds were estimated being incidentally killed for the settings analysed from September 2003 to August 2006 by legal longliners in French EEZs of Crozet and Kerguelen. Two species were concerned: the white-chinned petrel, especially during the southern summer (84–91% depending on the year), and the grey petrel, representing the main incidental capture during the southern winter. The incidental mortality reported here is the highest amongst the CCAMLR statistical areas (SC-CAMLR 2006) and represents a recurrent situation in recent years (Delord et al. 2005). Nevertheless, the situation has globally improved since the early 2000s (Delord et al. 2005), with a decrease in incidentally killed seabirds irrespective of the area or the season from 0.63 to 0.06 birds per 1,000 hooks, and the disappearance of albatross mortality. This coincided with the implementation of additional mitigation measures (closing period, gear modifications and the use of greater number of scaring line spreading). Nonetheless, further reduction in incidental mortality is needed, particularly for the grey petrel, for which incidental mortality has not been significantly reduced.

In the white-chinned petrel, more males were killed than females; such sex-biased mortality may have important effects on population dynamics (Mills and Ryan 2005). Sex-biased mortality in bycatch was observed for several Procellariiform species: a bias toward females was reported for wandering albatrosses (*Diomedea exulans*) and grey petrels (Bartle 1990; Weimerskirch and Jouventin 1987) and toward males for white-chinned petrels, grey-headed albatrosses and yellow-nosed albatrosses (Nel et al. 2002;

Ryan and Boix-Hinzen 1999). Although several explanations were suggested, such as sexual segregation of foraging areas or intraspecific competition on foraging grounds excluding females of smaller body size, further studies are needed to understand the ecological or behavioural causes underlying these biases.

The two steps analyses (considering first the occurrence versus absence of mortality and then focusing only on settings with incidental mortality) allowed us to assess the effect of a number of factors on the abundance of a rare and patchy event: a seabird incidental mortality. By separately modelling the probability of presence and the abundance given presence, we learned more about the system than we would using a single model for abundance. Furthermore, this approach is well-worth considering, when analysing skewed data with a large proportion of zeros. Our results showed clearly that the decrease in seabird bycatch over the period was mainly due to an important decrease in the occurrence of mortality (Kerguelen, from 35% of the settings with mortality during 2003/2004 to 10% during 2005/2006; Crozet, from 21% during 2003/2004 to 0.5% during 2005/2006). However, during the same period, we failed to detect any trend in numbers caught per setting (even an increase between last 2 years; Table 4, 6). This suggest that mitigation measures were effective for the factors implicated in the occurrence of bycatch (see Tables 3, 5), and represent valuable management tools.

Although the Patagonian toothfish longline fishery in the French EEZs showed high incidental mortality during the study period, it is barely conceivable ethically to properly test and evaluate independently the parameters implicated and specifically the mitigation measures used, which evolved and were gradually implemented. Seabird incidental mortality in longline fisheries is a known entanglement between risks for seabirds (through their distribution in time and space), the fishing practices and environmental conditions that might impact them (Brothers et al. 1999b; Delord et al. 2005; Gandini and Frere 2006; Klaer and Polacheck 1998). Consequently, we considered different factors in our analysis without a priori idea of which mitigation measure was the most effective. The results need to be cautiously interpreted due to unbalanced samples and great number of factors implicated. Our results suggest that factors reflecting risk for seabirds (temporal: season or phenology and spatial: area) were the most associated with incidental mortality for the two species caught. Furthermore, we found that mitigation measures and practices used by the vessels (operational factors: integrated weight mainline, number of scaring line, number of hooks hauled, environmental factors: wind/vessel angle, moon brightness) influenced these risks of mortality.

Risk areas and times: temporal and spatial variables affecting incidental mortality

For both species, incidental mortality peaked during the breeding season as found for the period 2001–2003 (Delord et al. 2005). The mortality of white-chinned petrels and grey petrels, respectively, peaked from September to March and from March to October, corresponding to the species' specific breeding seasons, with a marked peak during the brooding period. These seasonal differences may correspond to reproductive constraints. At Crozet, white-chinned petrels have higher energetic demands during breeding and are likely to interact with the several longline vessels during foraging trips (Catard et al. 2000; Weimerskirch et al. 1999; Weimerskirch et al. unpublished data). Nevertheless, non-breeders or failed breeders may also be at a risk, and potentially represent a large proportion of the individuals incidentally killed (Barbraud et al. 2008). Juvenile and immature birds are known to visit colonies during the reproductive season (Brooke 1990; Weimerskirch and Jouventin 1987) and may be more sensitive to incidental mortality due to their inexperience (Barbraud et al. 2008; Bregnballe and Frederiksen 2006; Weimerskirch et al. 1997). More detailed information on the at-sea distribution, breeding status and origin of birds incidentally killed is needed to accurately estimate the impact of incidental mortality on population dynamics.

Data on foraging trips of white-chinned petrels rearing chicks or incubating at the Crozet and Kerguelen islands (Catard et al. 2000; Weimerskirch et al. 1999; Pinaud and Weimerskirch 2007; Weimerskirch et al. unpublished data) indicate that birds seem to have long-range foraging strategies. They have a wide at-sea distribution and use distant foraging zones from their breeding ground. Thus, even if an overlap exists with longliners' fishing grounds, interactions with vessels appear of lesser importance in the Kerguelen than in the Crozet EEZ (Catard et al. 2000; Weimerskirch et al. unpublished data).

Foraging zones of grey petrels breeding at Kerguelen and Crozet are not yet known. Indirect evidence derived from at-sea surveys, recoveries of banded birds by longliners (i.e. direct evidence of mortality associated with fishery activities) and conventional dietary analyses (Stahl et al. 1996; Cherel et al. unpublished data; Weimerskirch et al. unpublished data) suggests that some breeding birds attend and interact with longliners.

The observed incidental mortality was higher at Kerguelen, irrespective of the zone considered, than at Crozet (Table 3). For the white-chinned petrel, this difference might be partly explained by different population sizes: the Kerguelen population is probably 4–5 times larger than the Crozet one (Barbraud et al. 2006, 2008, 2009). However, this does not explain the local variability of incidental mortality observed between the Kerguelen zones, which may be linked to other factors such as local variations in population densities.

Spatial variation of incidental mortality of grey petrels does not appear to vary with the number of breeding pairs (Table 7), with similar sized breeding populations between Kerguelen and Crozet Islands (Barbraud et al. 2006, 2009). Consequently, we can suspect that incidental mortality may have a larger impact on the Kerguelen than on the Crozet population.

Operational variables affecting incidental mortality

Integrated weight longlines showed the lowest incidental mortality. Increasing line sink rates is an effective mitigation measure (Anderson and McArdle 2002; Boggs 2001; Brothers et al. 2001; Robertson et al. 2006) and was ascribed to decrease the chance of interactions between seabirds and fishing gear by achieving a faster-line sink rate (Robertson et al. 2006).

The higher incidental mortality was observed with combined longlines compared with integrated weight or, surprisingly, to none integrated weight longlines. This may result from a loss of efficiency of the integrated weight line section due to manual addition of weights by the crew on non-integrated weight sections, resulting in fits and starts during setting inducing sudden fall in sinking rate.

The use of bird-scaring lines deployed astern during line setting is another associated mitigation measure frequently used to reduce interactions between seabirds and fishing gear (Brothers et al. 1999a; see Bull 2007 for review). We found that a higher number of scaring lines deployed tended to reduce incidental mortality for the two species concerned. Nevertheless, more detailed data on aerial coverage of the scaring lines and on line sink rate are necessary to precisely evaluate the efficiency of these mitigation measures.

The number of hooks hauled per mainline appeared to affect the mortality: the higher the number of hooks, the higher the mortality of white-chinned petrels. This suggests that longlines remain attractive and sufficiently accessible for birds during setting. The attractiveness of the vessels is probably linked to the fisheries waste (offal, fish heads and discards) discharging throughout most of the time that the vessel is on the fishing grounds, except during setting (Watkins et al. 2008; Waugh et al. 2008).

Environmental variables affecting incidental mortality

Our results indicate that increased moon brightness corresponded to a higher mortality. Some studies concluded along this line (Barnes et al. 1997; Brothers et al. 1999b; Gandini and Frere 2006; Moreno et al. 1996) while others

Table 7 Number estimated of breeding pairs, observed incidental mortality, percentage of white-chinned and grey petrels populations incidentally killed and fishing effort during 2003/2004, 2004/2005 and 2005/2006 in French EEZs

	Estimated number of breeding pairs	Accuracy	Estimated incidental mortality (number of birds/year)[d]			Percentage of population incidentally killed/year[e]			Fishing effort (Number of hooks hauled)		
			2003/2004	2004/2005	2005/2006	2003/2004	2004/2005	2005/2006	2003/2004	2004/2005	2005/2006
Crozet											
White-chinned petrel	26,471–49,718[a]	High	303	213	170	0.15	0.10	0.08	5,447,651	4,857,900	6,383,991
Grey petrel	2,000–5,000[b]	Low	16	28	9	0.2	0.35	0.11			
Kerguelen											
White-chinned petrel	186,000–297,000[c]	High	2,694	4,098	1,873	0.28	0.43	0.19	27,676,730	26,589,386	25,574,881
Grey petrel	1,900–5,600[c]	High	254	418	370	2.53	4.16	3.68			

[a] Barbraud et al. (2008)

[b] Weimerskirch et al. (1989)

[c] Barbraud et al. (2009)

[d] Estimated from bycatch used in the analyses of incidental mortality taking into account for the protocol used, logbook during 2003/2004, fishery observers during 2004/2005 and 2005/2006, the percentage of observation of hooks hauled and the ratio number of hooks set/number of hooks hauled

[e] Calculated according to minimum breeding population size estimate

failed to detect any effect (Gales et al. 1998; Weimerskirch et al. 2000).

The mortality was also affected by climatic conditions (wind/vessel angle or Beaufort) during setting, which is probably connected to a weakening of the efficiency of mitigation measures, e.g. by reducing sinking speed or aerial coverage of scaring lines (Brothers et al. 1999b).

The efficiency of night settings as a mitigation measure to alleviate incidental mortality of seabirds is a known fact for albatross species, but is much lower in the case of nocturnal feeders and divers, such as white-chinned petrels and grey petrels (Cherel et al. 1996; Delord et al. 2005; Huin 1994; Weimerskirch et al. 2000). Closing specific periods, if not the ideal solution regarding illegal unreported and unregulated (IUU) fisheries, has considerably contributed to reduce incidental mortality (Gilman et al. 2005; Delord et al. 2005). Although closure has been implemented to provide an immediate solution for reducing bycatch by temporarily reducing or displacing fishing effort, closure can also introduce additional problems such as the presence of IUU fishing vessel when the legal fishery is closed (Roche et al. 2007; Tuck et al. 2003). Nevertheless, during the last decade, incidental mortality levels of white-chinned petrels and especially grey petrels in the French EEZs have been demonstrated to be demographically unsustainable (Barbraud et al. 2008; Barbraud et al. unpublished data). The conservation status of these two species is worrying. The white-chinned petrel is classified as "Vulnerable" IUCN Red List category because of inferred rapid declines, although few reliable estimates of historical populations exist and few monitoring studies are in place to detect changes (Martin et al. 2009; Barbraud et al. 2008, 2009; Berrow et al. 2000; Reid and Catry 2006). However, given likely recent massive mortality in fisheries (Delord et al. 2005; IOTC 2005; 2006; 2007; Petersen 2006; Petersen et al. 2007; SC-CAMLR 2006; Watkins et al. 2008) and its susceptibility to predation on the land by introduced predators and loss of breeding habitat, a rapid and substantial population decrease is almost inevitable (BirdLife International 2005). The grey petrel is classified as "Near Threatened" for the same reasons affecting white-chinned petrels (BirdLife International 2004). Although few reliable estimates and trends of breeding populations are available, the population of grey petrels breeding in Southern French Territories probably represents the main part of the regional population (Southern Indian Ocean) (Barbraud et al. 2009; ACAP 2005; del Hoyo et al. 1992; Jouventin et al. 1984; SC-CAMLR 2002; Weimerskirch et al. 1989), and incidental mortality concerned a larger proportion of the breeding population than for the white-chinned petrel (Table 7). A closure period during the peak mortality period of grey petrels would probably be an effective mitigation measure.

The sympatric breeding of white-chinned petrels and grey petrels at Kerguelen make it particular in the CCAMLR area. The closure of the fishery in summer would report fishing effort in winter, and, thus, threaten to a larger extent the grey petrel population that is already seriously affected, much more than white-chinned petrel population.

Therefore, a suite of appropriate and evaluated measures should be used in combination to mitigate seabird bycatch. To arrive at a satisfactory compromise between fishery and seabird conservation interests remains particularly challenging. This probably depends on an extended dialogue between the parties: national administration, fishing lobby, fishing masters and scientists. Recent efforts concerning mitigation measures were obviously efficient in reducing significantly incidental mortality (mainly of white-chinned petrels; SC-CAMLR 2008), abating bycatch of grey petrels must be considered a future conservation priority.

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