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Diving behaviour of white-chinned petrels and its relevance for mitigating longline bycatch

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Abstract The white-chinned petrel (*Procellaria aequinoctialis*) is the seabird species most commonly killed by Southern Hemisphere longline fisheries. Despite the importance of diving ability for mitigating longline bycatch, little is known of this species' diving behaviour. We obtained data from temperature–depth recorders from nine white-chinned petrels breeding on Marion Island, south-western Indian Ocean, during the late incubation and chick-rearing period. Maximum dive depth (16 m) was slightly deeper than the previous estimate (13 m), but varied considerably among individuals (range 2–16 m). Males dived deeper than females, and birds feeding chicks dived deeper than incubating birds, but dive rate did not differ between the sexes. Time of day had no significant effect on dive depth or rate. Our findings will help to improve the design and performance of mitigation measures aimed at reducing seabird bycatch in longline fisheries, such as the calculation of minimum line sink rates and optimum aerial coverage of bird-scaring lines.

Keywords Dive depth · Dive duration · Temperature–depth recorders · Seabirds · Bird-scaring lines

Introduction

The white-chinned petrel (*Procellaria aequinoctialis*) is the seabird species most commonly killed as bycatch on

longlines in the southern Ocean and adjacent temperate waters (DeLord et al. 2005; Moreno et al. 2006; Robertson et al. 2006; Petersen et al. 2009a, b; Ryan et al. 2012). During summer, breeding birds disperse widely throughout the southern Ocean, foraging from the subtropics to the pack ice (Weimerskirch et al. 1999). Non-breeding birds range into the tropics along western boundary currents (Marchant and Higgins 1990), exposing them to a wide range of longline fisheries. Despite having a population of more than one million pairs (Ryan et al. 2012), they are listed as vulnerable by the IUCN because of the high levels of bycatch and the evidence that some populations are decreasing (Birdlife International 2014).

To help reduce seabird bycatch on longlines, it is important to understand their diving capabilities because mitigation measures mainly protect baited hooks until they sink below the birds' diving range. Knowledge of diving ability is needed to design effective bird-scaring lines as well as to determine minimum line sink rates and maximum setting speeds (Robertson 2000). This is especially important for white-chinned petrels, because they have been implicated in the bycatch of albatrosses and other large, shallow-diving species by bringing baited hooks to the surface, where the petrels are displaced by the larger species (Jimenez et al. 2012). White-chinned petrels also are one of the few species that gain little if any benefit from restricting line setting to the night, because they appear to be equally proficient at foraging at night as during the day (Harper 1987; Barnes et al. 1997; Nel et al. 2002).

Currently, little is known of white-chinned petrel diving behaviour. The only direct measure of diving ability to date used capillary depth gauges to estimate maximum dive depths (Huin 1994: maximum 12.8 m; average maximum for 11 birds = 6.2 m). However, Huin (1994) left gauges on birds for up to 12 days, and the accuracy of capillary

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gauges decreases with the number of dives (Burger and Wilson 1988). Also, these depth gauges give no indication when the deepest dive takes place or dive velocity in the water column. Nocturnal diving ability is of particular interest because setting lines at night is one of the key mitigation measures to reduce seabird bycatch in southern Ocean fisheries (Murray et al. 1993; Cherel et al. 1996). The white-chinned petrel is one of the most nocturnal of petrels (Harper 1987; Mackley et al. 2011), and bycatch rates on longlines set at night are similar to those set during the day (Barnes et al. 1997). White-chinned petrel activity apparently increases around full moon, but this has only been demonstrated during the non-breeding season (Mackley et al. 2011).

More detailed information on the diving behaviour of seabirds can be obtained from digital temperature–depth recorders (TDRs), with data now available for a range of petrels and shearwaters (Weimerskirch and Sagar 1996; Burger 2001; Ronconi et al. 2010). In this study, we report the diving behaviour of breeding white-chinned petrels using these digital loggers.

Methods

The diving ecology of white-chinned petrels was studied using G5 Cefas TDRs (35.5 × 11.5 mm, 2 Mb memory) that weigh 2.7 g (<0.3 % of adult body mass; Marchant and Higgins 1990). Loggers were attached to the back feathers in the best possible way to reduce drag while in the water. Simple TDR deployments taped the logger lengthwise on the bird's back. Some TDRs were deployed in tandem with a compact global positioning satellite system (GPS) logger (see full details below) housed in a heat shrink tube, which resulted in a streamlined waterproof capsule. The TDR was glued laterally along the rear edge of the capsule, thereby not increasing the frontal surface area or adding to the drag effect. The entire rectangular-shaped device (31 mm wide, 59 mm long, 13 mm high, ~15 % of the cross sectional width of the bird) was then taped to the birds' back feathers, and the feathers in front of the device were combed over the device (covering >50 % of device) to further reduce drag.

The TDR loggers were programmed using G5 Host (Version 4.0) to sample depth and temperature every 2 s at 12 bit resolution, providing accuracies of ±1 m and ±0.1 °C, respectively. This relatively coarse sampling frequency was selected to sample throughout the long foraging trips (up to 13 days during incubation). Adult white-chinned petrels were captured in their breeding burrows on sub-Antarctic Marion Island (46°52'S, 37°51'E) in the southern Ocean (Fig. 1). TDRs were attached to the birds' back feathers with black Tesa tape,

which allows them to be removed with minimal damage to the plumage (Wilson et al. 1997). Handling lasted <5 min, with weighing and measuring done on device retrieval. Birds were sexed by measuring their culmen length and bill depth at the gonys to the nearest 0.1 mm with Vernier callipers (Ryan 1999). TDRs were deployed on six petrels (five females, one male) during the late incubation period (18 November–5 December 2012) and six petrels (two females, four males) during the chick-rearing period (1 January–6 February 2013). Nest burrows were checked regularly thereafter via inspection hatches until the equipped bird returned. During the chick-rearing phase, when adults do not remain at the nest for long, returning adults were trapped in the burrow by fitting a one-way flap to burrow entrances.

To assess where birds foraged, 24 birds were tracked using GPS loggers (CatTraq™, 16 Mb memory, 230 mA lithium-ion battery, Mr Lee Technologies); 11 during incubation and 13 during chick rearing. Nine GPS devices were retrieved with data during incubation and 11 during chick rearing. These loggers were customised (IPHC-DEPE, Strasbourg, France) by removing the original packaging and replacing the main switch button with a reed switch to give a smaller, lighter device (45.7 × 30.5 × 12.7 mm, 25 g). The GPS loggers were programmed using @trip PC (Version 2.0) to sample a position every 60 min. One incubating bird and six chick-rearing birds also were equipped with a TDR (total mass of both devices ~2.5 % body mass), but data from both devices were only obtained from four birds during chick rearing.

TDR data were analysed using IGOR Pro (Wavemetrics Inc., USA, 2008, Version 6.04) and were corrected for surface drift (the slight inaccuracy in the calculation of the

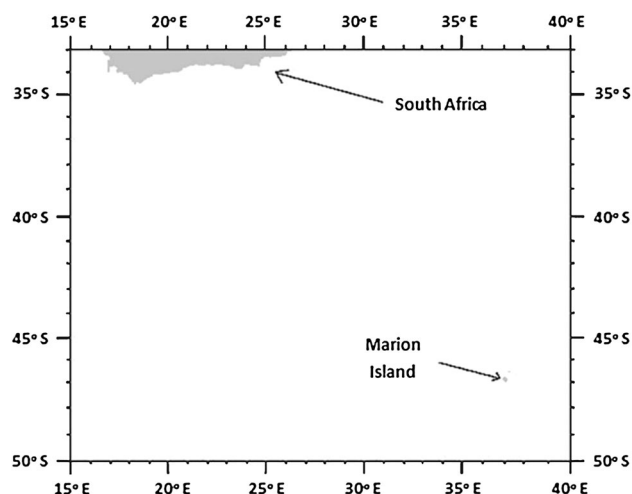


Fig. 1 Map showing location of Marion Island in the south-western Indian Ocean in relation to the south coast of South Africa

Table 1 Comparison of generalised linear mixed models (GLMM) explaining dive depths and dive durations of white-chinned petrels using sex, breeding stage and time of day/lunar luminance as explanatory variables and individual bird as a random effect

Model	df	Loglikelihood	AICc	ΔAICc	Weight
<i>All dives (to compare time of day)</i>					
Dive depth	–	–	–	–	–
Breeding stage	4	–663.919	1,336.0	0.00	0.237
Breeding stage + Sex	5	–663.148	1,336.5	0.53	0.182
Time of day + breeding stage	5	–663.246	1,336.7	0.72	0.165
Sex	4	–664.499	1,337.1	1.16	0.133
Time of day + breeding stage + sex	6	–662.609	1,337.5	1.53	0.110
Null	3	–666.142	1,338.4	2.39	0.072
Time of day + Sex	5	–664.206	1,338.6	2.64	0.063
Time of day	4	–665.757	1,339.7	3.68	0.038
Dive duration	–	–	–	–	–
Breeding stage + Sex	5	–816.014	1,642.2	0.00	0.300
Time of day + breeding stage + sex	6	–815.399	1,643.1	0.85	0.196
Sex	4	–818.191	1,644.5	2.28	0.096
Breeding stage	4	–818.216	1,644.6	2.33	0.093
Null	3	–819.297	1,644.7	2.44	0.089
Time of day	4	–818.406	1,644.9	2.71	0.077
Time of day + Sex	5	–817.395	1,645.0	2.76	0.075
<i>Night dives only (to compare effect of lunar luminance)</i>					
Dive depth	–	–	–	–	–
Breeding stage	4	–80.472	169.9	0.00	0.473
Breeding stage + sex	5	–79.693	170.8	0.95	0.294
Sex	4	–81.954	172.9	2.97	0.107
Null	3	–83.282	173.1	3.23	0.094
Lunar luminance	4	–84.260	177.5	7.58	0.011
Breeding stage + lunar luminance	5	–83.176	177.8	7.92	0.009
Breeding stage + Lunar luminance + sex	6	–82.178	178.5	8.56	0.007
Lunar luminance + sex	5	–83.608	178.7	8.78	0.006
Dive duration	–	–	–	–	–
Breeding stage + sex	5	–113.809	239.1	0.00	0.281
Sex	4	–115.217	239.4	0.30	0.241
Breeding stage	4	–115.271	239.5	0.41	0.228
Null	3	–116.509	239.6	0.50	0.219
Breeding stage + lunar luminance + sex	6	–115.571	245.2	6.16	0.013
Breeding stage + lunar luminance	5	–117.249	246.0	6.88	0.009
Lunar luminance + sex	5	–117.900	247.3	8.18	0.005
Lunar luminance	4	–119.394	247.7	8.66	0.004

surface of the water). To exclude noise in the data, ‘dives’ <1 m were discarded and dives to 1–2 m were also discarded if the baseline was particularly noisy. The relatively coarse sampling interval (2 s) reduced our ability to discriminate short dives. Maximum dive depths and dive durations were recorded, although both estimates were conservative due to the 2-s sampling interval. Dive profiles were divided into V-shaped dives and U-shaped dives that had a bottom phase (defined as the time at or near

maximum depth of dive where dive rate was $<0.25 \text{ m s}^{-1}$, Kato et al. 2006). Due to the coarse sampling rate, descent and ascent rates were only estimated for dives $>5 \text{ m}$ deep.

We estimated dive frequency in relation to diel cycles and moon phase. Sunrise/set times as well as moon phase and moonrise/set times were calculated based on GPS coordinates for the four chick-rearing birds equipped with GPS loggers. However, the time of sunrise/set and moonrise/set was unknown for incubating birds given

uncertainty regarding their locations. Approximate latitudinal location was inferred from sea surface temperature (SST) data recorded by the TDRs. All incubating white-chinned petrels tracked with GPS loggers visited the southern Benguela system or Agulhas Current off South Africa, where SST is 17–21 °C (range 32–48°S and 18–40°E). The five incubating birds equipped with TDRs probably also foraged in these waters, as most dives occurred where SST was >17 °C. During chick rearing, three birds visited the South African continental shelf, while one travelled south into Antarctic waters (range 32–63°S, 18–48°E). Moon phase was placed into three equal categories based on percentage illumination (0–33, 34–66 and 67–100 %), but we could not assess the effect of cloud cover on lunar illumination.

All statistics were analysed using R (version 2.15.0, R Foundation for Statistical Computing 2012). Means are reported \pm 1 standard deviation. Generalised linear mixed models (GLMM) with a Gaussian distribution using a logarithmic link function were used to determine the influence of various explanatory variables on dive duration and dive depth, with individual bird as the random effect. These models were created using the NLME package (Linear and Nonlinear Mixed Effect Models). Separate models were created to test the effect of time of day (day/night) and lunar luminance (percentage) on dive depth and duration. The models which incorporated time of day included all dives ($n = 296$), while the models which incorporated lunar

luminance only included those dives undertaken during the night, after moonrise and before moonset ($n = 47$). Model averaging was used to select most influential models along with Akaike's information criterion (Tables 1, 2). To relate dive duration to dive depth, we tested both linear and exponential models and selected the model that gave the best coefficient of determination (r^2). *T* tests and analysis of variance (ANOVA) were used to determine significance of dive rates between sex and stage of breeding.

Results

Loggers were recovered from 10 of the 12 white-chinned petrels 13–39 days after deployment, but data were only retrieved from nine TDRs: five from incubators and four from birds provisioning chicks (Table 3). Due to battery life/memory limitations, diving data were recorded for 9.2 ± 3.1 days (range 5–13 days), sampling 1–3 foraging trips per bird. The number of dives recorded per bird was 32.9 ± 23.6 dives at an average rate of 3.6 ± 2.3 dives day⁻¹ (Table 3). There was no difference in trip duration, dive frequency or dive depth between birds equipped with both TDR and GPS devices and those birds just carrying the much smaller TDRs. Bird A only made two dives in 12 days, but this small number of dives apparently was not due to device influence, because this bird only carried a TDR.

Table 2 The average of the best-fitting models weighted by AIC ($\Delta AICc < 4$), showing the effects of the different variables on both dive depth and duration of white-chinned petrels with separate models to assess time of day (based on all dive data) and lunar luminance (restricted to nocturnal dives)

Variable	Estimate	SE	Adjusted SE	<i>z</i>	Pr (> <i>z</i>)
Dive depth (time of day)	–	–	–	–	–
Intercept	3.316	0.646	0.648	5.118	< 0.001
Breeding stage (incubation)	–1.079	0.622	0.759	1.421	0.155
Sex (male)	0.633	0.712	0.857	0.739	0.460
Time of day (night)	–0.387	0.301	0.303	1.280	0.201
Dive duration (time of day)	–	–	–	–	–
Intercept	3.983	1.095	1.097	3.630	< 0.001
Breeding stage (incubation)	1.356	1.083	1.306	1.038	0.299
Sex (male)	1.376	1.082	1.306	1.055	0.292
Time of day (night)	–0.503	0.506	0.508	0.990	0.322
Dive depth (lunar luminance)	–	–	–	–	–
Intercept	3.355	0.784	0.802	4.184	< 0.001
Breeding stage (incubation)	–1.358	0.792	0.998	1.360	0.174
Sex (male)	0.4166	1.145	1.456	0.286	0.775
Dive duration (lunar luminance)	–	–	–	–	–
Intercept	3.981	1.192	1.229	3.239	0.001
Breeding stage (incubation)	0.241	1.682	2.169	0.111	0.981
Sex (male)	–0.326	1.721	2.220	0.146	0.884

Most dives were <5 m (87 %), with 95 % of dives <8 m (Fig. 2). Maximum dive depth varied considerably among individuals (range 2–16 m; Table 3) and was influenced in part by the number of dives sampled:

$$\text{dive depth (m)} = 2.57 \times \ln(\text{number of dives}) + 0.806 (r^2 = 0.42).$$

Four of nine birds made dives >10 m deep, with the deepest diving individual having 31 % of dives >5 m deep. Most dives were V-shaped (89 %, $n = 296$). Dive profile had no effect on dive depth ($t = 0.44$, $P = 0.66$), but U-shaped dives (average = 7.4 ± 4.5 s) lasted longer than V-shaped dives (average = 4.3 ± 3.6 s, $t = 5.51$, $P < 0.001$). Mean dive duration was only 4.6 s (maximum = 22 s; Table 3). Dive duration was related to maximum dive depth:

$$\text{dive duration (s)} = 0.548 \times \text{dive depth (m)} + 0.528 (r^2 = 0.63).$$

This relationship was strengthened further if U-shaped dives were excluded ($r^2 = 0.69$). Descent and ascent rates on deep dives (>5 m) averaged 1.58 ± 0.53 and 1.50 ± 0.48 m s⁻¹, respectively ($n = 38$).

Overall 63 % of dives occurred during the day, but this was similar to the average day length at the time of the study (58–65 % depending on latitude and date). There was no difference in dive rate at night (0.15 dives h⁻¹; $n = 110$) or during the day (0.11 dives h⁻¹; $n = 186$; T test: $t_{294} = 1.734$, $P = 0.30$; Fig. 3). Time of day had a minor influence on average maximum dive depth with a greater influence on average maximum dive duration; birds made slightly longer dives during the day than at night

(Tables 1, 2). Moon phase had little influence on dive duration, dive depth or dive rate (but statistical power was low due to the small total number of night dives).

Although none of the variables tested had particularly strong effects on dive duration or dive depth (when either time of day or lunar luminance was included), stage of breeding had the most influence on both dive depth and dive duration, with birds provisioning chicks diving deeper and for longer than incubating adults (Table 2). Sex also influenced dive duration, with males diving for longer than females (Table 2). However, most birds sampled during incubation were female (4 of 5), whereas most birds sampled during chick rearing were male (3 of 4). A greater proportion of dives made by females were U-shaped

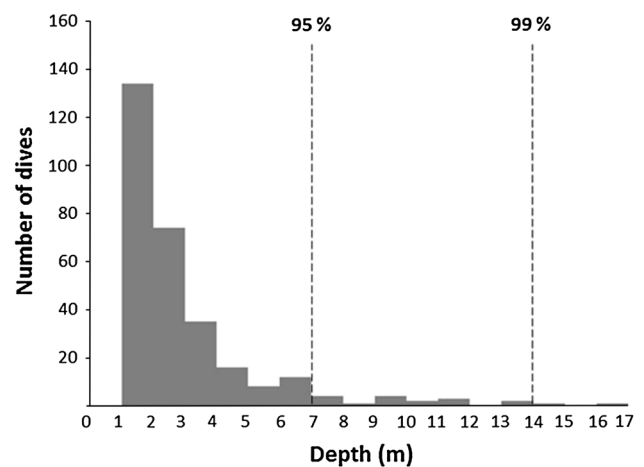


Fig. 2 Frequency of the maximum dive depths of white-chinned petrels. Dashed lines show 95 and 99 % dive depths

Table 3 Diving behaviour of white-chinned petrels during incubation and chick-rearing periods

Bird (sex)	Body mass (g)	n days	Dives per day		Dive duration (s)		Dive depth (m)	
			Maximum	Mean \pm SD	Maximum	Mean \pm SD	Maximum	Mean \pm SD
Incubation	1,272	42	21	4.05 \pm 5.39	22	4.8 \pm 4.0	13.4	2.4 \pm 1.6
A (F)	1,180	12	1	0.17 \pm 0.39	2	2.0 \pm 0.0	2.1	1.7 \pm 0.4
B (F)	1,220	9	21	6.78 \pm 7.12	22	5.3 \pm 3.9	6.8	2.6 \pm 1.4
C (F)	1,290	10	20	7.60 \pm 6.04	22	3.8 \pm 3.2	13.4	2.1 \pm 1.7
D (M)	1,310	5	7	2.80 \pm 2.68	20	6.6 \pm 6.0	7.5	2.9 \pm 2.2
E (F)	1,360	6	7	2.83 \pm 2.64	16	6.3 \pm 4.3	6.5	2.8 \pm 1.6
Chick rearing	1,240	41	25	3.07 \pm 5.25	20	4.5 \pm 3.8	16.1	3.6 \pm 2.9
F (F) ^a	1,260	9	25	4.44 \pm 7.81	14	4.4 \pm 3.5	10.2	3.5 \pm 2.9
G (M) ^a	1,290	13	10	2.46 \pm 3.53	20	6.3 \pm 5.3	16.1	4.6 \pm 3.9
H (M) ^a	1,210	13	11	2.38 \pm 3.59	6	3.5 \pm 1.6	6.1	2.4 \pm 1.4
I (M) ^a	1,200	6	19	3.83 \pm 7.47	10	3.1 \pm 1.8	11.4	3.1 \pm 2.2
All birds	1,258	83	25	3.57 \pm 5.31	22	4.6 \pm 3.9	16.1	2.9 \pm 2.4

^a Birds equipped with a TDR and GPS

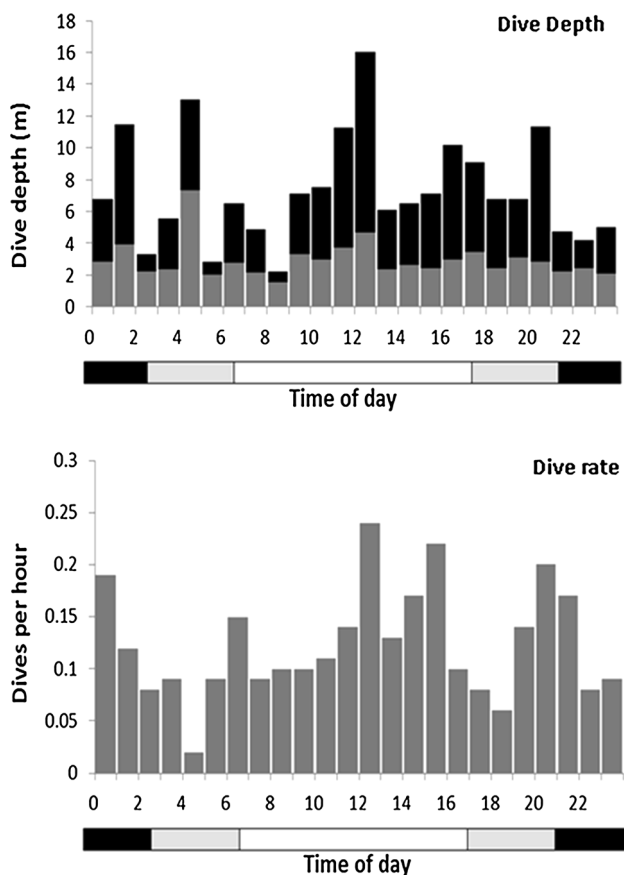


Fig. 3 Dive depth and rate of white-chinned petrels in relation to time of day. Grey bars show mean maximum dive depth; black bars maximum dive depth. Scale bar indicate approximate light levels: black night, white day, grey uncertain (given uncertainty regarding the bird positions)

compared to dives by males, and sex had no effect on dive rate ($t_8 = 0.99$, $P = 0.35$).

Discussion

There are relatively few observations of diving by white-chinned petrels, which seize most prey close to the surface (Marchant and Higgins 1990). Harper (1987) reported that dives averaged only 2.4 s (range 0.4–6.3 s), appreciably shorter than the longest dives recorded in this study (22 s). The maximum dive depth (16.1 m) was slightly greater than the depth estimated with capillary depth gauges (12.8 m; Huin 1994). The stage of breeding influenced diving behaviour, with birds provisioning chicks (and thus facing a greater energy demand) diving deeper than incubating birds (cf. Shaffer et al. 2003). However, Huin (1994) also studied birds provisioning chicks, so breeding stage is unlikely to account for the difference in dive depth between these studies. Estimates of maximum dive depths are

sensitive to sampling effort, and although the numbers of birds studied (9 vs. 11) were similar, the average duration of deployment in our study at Marion Island (9.2 days) was greater than that at Bird Island, South Georgia (5.8 days). Huin (1994) assumed birds dived at 2 m s^{-1} , whereas our direct measurements were less, at around 1.5 m s^{-1} .

The maximum dive depth of the white-chinned petrel is more than double that of the only other *Procellaria* petrel whose maximum dive depth has been studied. Using capillary depth gauges, Freeman et al. (1997) estimated that Westland Petrels (*P. westlandica*) dived to 7.6 m. Neither species dives anywhere near as deep as some shearwaters (Table 4). Despite these large differences in dive depths, Kuroda (1954) noted osteological similarities between *Procellaria* petrels and shearwaters (*Calonectris* and *Puffinus*). Dive depth varies greatly among shearwaters, with several of the larger *Puffinus* species reaching depths of >60 m, whereas smaller species dive to more than 20 m (Table 4). By comparison to the *Puffinus* shearwaters, which are well designed for underwater foraging (Brown et al. 1978), *Calonectris* shearwaters are adapted more for efficient gliding flight than underwater swimming (Brown et al. 1978) and barely reach depths of 5 m (Table 4).

Harper (1987) observed more dives by white-chinned petrels at night than during the day, but activity data from GLS loggers suggest that they spend slightly more time resting at night than during the day (Mackley et al. 2011). We found no significant difference in diving rate between day and night, and at least some night dives exceeded 10 m. This nocturnal diving ability explains why white-chinned petrels continue to be caught in large numbers by many longline fisheries despite a ban on line setting during the day in most fisheries (Barnes et al. 1997; Petersen et al. 2009a). The deeper diving depths of male white-chinned petrels might contribute to the strong male-bias in longline bycatch of breeding adults (Ryan and Boix-Hinzen 1999, Nel et al. 2002) and probably is linked to the larger size of males than females (cf. Lewis et al. 2002; Cook et al. 2007). The short duration of most dives explains the paucity of U-shaped dives, which typically occur when birds actively pursue prey (Shepard et al. 2010).

Current best practice mitigation measures for pelagic longline fisheries in the southern Ocean aim to ensure that lines are properly weighted, setting only occurs at night and that bird-scaring lines are used during line setting (Melvin et al. 2014). Lines should sink to a depth of 5 m while under the protection of bird-scaring lines (Melvin et al. 2014). This 5 m threshold was based on the maximum diving depth of white-chinned petrels (Melvin et al. 2011). However, results from the current study show that this depth should be deeper. White-chinned petrels occasionally dived over 5 m, and although very few dives

Table 4 Maximum dive depths of *Puffinus* and *Calonectris* shearwaters and *Procellaria* petrels estimated with temperature–depth recorders (TDR), capillary depth gauges (CDG) or direct observations (Obs)

Species (data source)	Technique	n	Max. dive depth (m)		Wingspan (cm)	Mass (g)
			Average	Maximum		
<i>Puffinus tenuirostris</i> ^a	CDG	22	29.4	70.6	100	800
<i>Puffinus griseus</i> ^{b,c}	TDR	60	14.1	69.9	105	950
<i>Puffinus carneipes</i> ^d	TDR	3	–	66.5	120	750
<i>Puffinus pacificus</i> ^{e,f}	CDG	19	14.0	66.0	99	510
<i>Puffinus opisthomelas</i> ^g	CDG	30	21.0	52.0	79	545
<i>Puffinus lherminieri</i> ^e	CDG	7	15.0	35.0	73	301
<i>Puffinus mauretanicus</i> ^h	CDG	3	–	26.0	93	565
<i>Puffinus baroli</i> ⁱ	CDG	5	14.8	23.1	67	187
<i>Puffinus gravis</i> ^j	TDR	2	14.9	18.9	115	950
<i>Calonectris diomedea</i> ^k	CDG	32	–	5.5	113	1,060
<i>Calonectris leucomelas</i> ^l	Obs	–	–	5.0	122	538
<i>Procellaria westlandica</i> ^m	CDG	3	3.2	7.6	140	1,200
<i>Procellaria aequinoctialis</i> ⁿ	CDG	11	6.2	12.8	147	1,390
<i>Procellaria aequinoctialis</i> ^o	TDR	9	8.9	16.1	147	1,390

Sources: ^aWeimerskirch and Cherel (1998), ^bShaffer et al. (2009), ^cWeimerskirch and Sagar (1996), ^dRayner et al. (2011), ^eBurger (2001), ^fPeck and Congdon (2006), ^gKeitt et al. (2001), ^hAguilar et al. (2003), ⁱNeves et al. (2012), ^jRonconi et al. (2010), ^kMougin and Mougin (1998), ^lOka (1994), ^mFreeman et al. (1997), ⁿHuin (1994), ^othis study. All wingspan and mass measurements from Onley and Schofield (2007) except *P. baroli* mass (Neves et al. 2012)

exceeded 10 m (Fig. 2), it is likely that a larger sample would yield dives close to 20 m, and this should be the minimum depth deemed safe for unprotected longline hooks. This would require a combination of longer bird-scaring lines, faster sink rates for hooks, and/or slower setting speeds. Wanless and Waugh (2010) calculated that if a vessel were to set lines at a speed of 6 knots (11.1 km h⁻¹) and achieving line sink rates of 0.3 m s⁻¹, then 97 % of hooks would have sunk to a depth of 10 m while under the protection of a bird-scaring line with 100 m aerial coverage. Branchlines with 60 g weight sank at 0.53 m s⁻¹ (Melvin et al. 2009), thus >75 % of weighted branchlines could have sunk to a depth of 15 m while under the protection of a bird-scaring line with 100 m aerial coverage, with a setting speed of 6 knots. Our findings also have important implications for new mitigation devices being trialled in pelagic longline fisheries, such as hook pods (a new mitigation measure that release hooks at a pre-determined depth, Sullivan 2011), and underwater bait setters (Robertson and Domingo 2011). Both devices need to take cognisance of the diving abilities of white-chinned petrels when determining the depth at which hooks and bait should be released.

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