



**SCIENTIFIC COMMITTEE  
TWENTIETH REGULAR SESSION**

Manila, Philippines  
14 – 21 August 2024

---

**Diving ecology of selected seabird species from the Southern and Northern  
Western and Central Pacific Ocean**

---

**WCPFC-SC20-2024/EB-IP-29**

Maria Düssler<sup>1</sup>, Rachael Orben<sup>2</sup>, Heiko Wittmer<sup>1</sup>, Olivia Rowley<sup>3</sup>, Igor Debski<sup>3</sup>,  
Scott A. Shaffer<sup>4</sup>, & Johannes H. Fischer<sup>3</sup>

---

<sup>1</sup> Victoria University of Wellington, Wellington, New Zealand.

<sup>2</sup> Oregon State University, Newport, USA.

<sup>3</sup> Department of Conservation, Wellington, New Zealand.

<sup>4</sup> San Jose State University, San Jose, USA.

\* Corresponding Author: [jfischer@doc.govt.nz](mailto:jfischer@doc.govt.nz).

## ABSTRACT

Bycatch is a prominent driver of seabird declines globally, including in commercial pelagic longline fisheries. Seabird diving depth and speed influences the effectiveness of several bycatch mitigation methods. However, most studies of seabird diving ecology were conducted outside of the Western and Central Pacific Ocean (WCPO), despite this area being a seabird hotspot. Additionally, the WCPO encompasses different seabird species assemblages between Hemispheres, which may result in key differences in diving ecology. Herein, we present preliminary results from two field studies and synthesise all available data on diving ecology for selected seabird species within the WCPO.

In the Southern WCPO, we studied the diving ecology of three *Procellaria* petrels by deploying time-depth recorders in New Zealand ( $n = 55$ ) to assess dive depths, durations, and descent rates. Black Petrels (*P. parkinsoni*) dived the deepest, with a maximum depth of 38.5 meters and 25.5% of dives >10 m depth. Westland Petrels (*P. westlandica*) dived up to 17.3 m, with 0.6% of dives >10 m, and showed the fastest descent rates at 1 m/s. White-chinned Petrels (*P. aequinoctialis*) reached maximum depths of 21.7 m, with 2.1% of dives >10 m. In the Northern WCPO, we studied the diving ecology of two *Phoebastria* albatrosses by deploying multi-sensor data loggers in Hawai'i, USA., ( $n = 63$ ) to assess dive depths, duration, and frequency. Laysan (*P. immutabilis*) and Black-footed Albatross (*P. nigripes*) had similar maximum diving depth of 6.0 m and 5.9 m, respectively. Deep diving behaviour was rare in both species, with only 2% of dives exceeding 2 m of depth, yet 74% of Laysan and 65% of Black-footed Albatrosses engaged in diving behaviour. Finally, the diving ecology synthesis puts these data into context and challenges the notion of fundamental diving ecology differences between Northern and Southern Hemispheres.

Our results show that hooks remain accessible to depths of 20 m for Black Petrels and 10 m for Westland and White-chinned Petrels in the Southern Hemisphere, and to 6 m for albatrosses in the Northern Hemisphere. Achieving protections of hooks in line with these depths would require combinations of weighted branch lines and tori lines and night setting or hook-shielding devices to reduce bycatch to low levels.

## INTRODUCTION

Seabird bycatch is a prominent driver of seabird declines, including in commercial pelagic longline fisheries (hereafter pelagic longline fisheries) (Richards *et al.*, 2024). Seabird bycatch mitigation measures designed for pelagic longline fisheries include tori lines, weighted branch lines, and night setting (e.g., Gilman *et al.*, 2005, Pierre 2023). For the former two measures to be effective, they must be directly informed by seabird diving ecology (Rollinson *et al.*, 2016; Frankish *et al.*, 2021). For example, known diving ability can inform depths to which hooks must be protected (Bell 2016) and dive descent rates can inform the sink rates of hooks (Gilman *et al.*, 2005). However, most studies of diving ecology of seabirds vulnerable to bycatch in pelagic longline fisheries were conducted outside of the Western and Central Pacific Ocean (WCPO), despite this area being a seabird hotspot. Additionally, the WCPO encompasses different seabird species assemblages between Hemispheres, which may result in key differences in diving ecology.

In the Southern Hemisphere of the WCPO, New Zealand hosts a large portion of the world's seabirds, including four of the five *Procellaria* petrels. This genus of large petrels is notoriously challenging for bycatch mitigation strategies, given their aggressive nature and deep-diving ability. This behaviour can result in hooks being returned to the surface and within the range of other seabirds (also known as secondary attacks; Jimenez *et al.*, 2012). Additionally, all *Procellaria* petrels are vulnerable to bycatch themselves (Bell 2016; Frankish *et al.*, 2021; Reid *et al.*, 2014; Rollinson *et al.*, 2016; Waugh and Wilson, 2017). The White-chinned Petrel (*P. aequinoctialis*) is the seabird most frequently killed in longline fisheries in the Southern Ocean and is listed as Vulnerable on the IUCN Red List (Frankish *et al.*, 2021; Phillips *et al.*, 2016; Rollinson 2014). Westland (*P. westlandica*) and Black Petrels (*P. parkinsoni*) are listed as Endangered and Vulnerable, respectively. Both New Zealand breeding endemics facing ongoing risks of bycatch in a range of fisheries including pelagic longlines (Bell 2016; Waugh and Wilson 2017). However, to date, most studies of *Procellaria* petrel diving ecology have been undertaken in other ocean basins (e.g., Frankish *et al.*, 2021; Reid *et al.*, 2014).

In the Northern Hemisphere of the WCPO, *Procellaria* petrels are absent, but the local seabird community is still composed of seabirds vulnerable to pelagic longline bycatch, *Phoebastria* albatrosses in particular. The *Phoebastria* genus consists of four species, three of which range within the northern WCPO. The Short-tailed Albatross (*P. albatrus*), listed as Vulnerable on the IUCN Red List, has an extensive and more northerly distribution favouring the shelf-habitats of the North Pacific (Suryan *et al.*, 2007; Orben *et al.*, 2018). The Laysan (*P. immutabilis*) and Black-footed (*P. nigripes*) albatross are both considered Near-threatened and range widely through the northern WCPO. Of these three species, Laysan and Black-footed Albatross are most commonly observed in bycatch (e.g., Gilman *et al.* 2003). However, albatrosses are assumed to exhibit little to no diving behaviour and thus only be at risk from hooks when these are close to the surface during setting or hauling. Given the absence of *Procellaria* petrels in the Northern WCPO, Northern Hemisphere albatrosses are perceived to be at relatively lower risk and hooks below 2 m of depth are expected to be out of reach of these species (Kazama *et al.*, 2019). However, only few studies have investigated the diving capability of albatross species in detail, with only one study examining the diving ecology of a Northern Hemisphere *Phoebastria* albatross (Kazama *et al.* 2019).

We here fill several major gaps in our current understanding of seabird diving ecology in the WCPO. Specifically, we present:

- I) Results from a field study investigating the diving ecology of three New Zealand *Procellaria* petrels,
- II) Results from a field study investigating the diving ecology of two *Phoebastria* albatrosses from Hawai'i, U.S.A., and
- III) A synthesis of all available data on diving ecology for seabird species vulnerable to pelagic longline bycatch that forage within the WCPO.

Combined, these studies allowed us to evaluate if the long-held notion that the different seabird species assemblages between Hemispheres in the WCPO results in key differences in diving ecology, and thus in fundamental differences in bycatch risk, and ultimately present information crucial to the ongoing review of WCPFC CMM 2018-03

## **METHODS**

### **Southern Hemisphere study on New Zealand *Procellaria* petrels**

To fill the data gap of diving ecology data from *Procellaria* petrels from the Southern WCPO, we studied Black, Westland and White-chinned Petrels in New Zealand.

#### ***Data collection***

Diving behaviour in seabirds can be investigated with the deployment of time-depth recorders (TDRs). These loggers record depth measurements at 1-2 second intervals from which dive depths, durations, and descent rates can be extracted once the tag is retrieved. We deployed TDRs on adult Black, Westland, and White-chinned Petrels during various phenological stages of the 2022-24 breeding seasons (Table 1). We fitted 21 Black Petrels with CT G5 long life TDRs (CEFAS Technology, Suffolk, UK) on Aotea/Great Barrier Island during incubation and early chick-rearing periods in the 2022/23 and 2023/24 breeding seasons, with a single redeployment in the 2023/24 chick-rearing to fledging period. We deployed a total of 24 TDRs on White-chinned Petrels during incubation and chick-rearing on the Moutere Mahue/Antipodes. Of these, 9 were DST milli F-TD TDRs (Star-ODDI, Garðabær, Iceland) deployed in the 2022 breeding season, and 15 were CEFAS G5 TDRs deployed in the following (2022/2023) breeding season. We deployed 45 TDRs on Westland petrels on the West Coast of the Te Wai Pounamu/South Island. Of these, 35 were CEFAS G5 TDRs deployed in the chick-rearing period of the 2022 breeding season ( $n = 20$ ) and the pre-laying to incubation period of the 2023 season ( $n = 15$ ), and 10 were Star-ODDI TDRs deployed in the 2022 breeding season during incubation. We programmed Star-ODDI TDRs to record depth at 2 s intervals, and the CEFAS G5 TDRs to record depth at 1 s intervals.

All TDRs were attached with a strip of rubber threaded through the TDR's custom casing and wrapped around the tarsus and all instrument packages were <3% of the body mass of each species. We removed the loggers by cutting the rubber strip with scissors. Following retrieval and data downloads, we obtained 13 White-chinned Petrel, 10 Black Petrel, and 32 Westland Petrel datasets for analyses (Table 1).

### Data analyses

All data filtering and analyses of dive depth, duration, and descent rates were performed using R Statistical Software (v4.4.1 2024). We extracted and cleaned the dive data using the package diveMove in R (Luque and Fried 2011; Luque, 2024). TDR pressure data can drift over time, causing recorded depths to deviate from true depths. Zero-offsetting filtering in diveMove corrects these deviations by adjusting the recorded depths to match the true depths by recalibrating surface measurements to 0 m depth. This method involves recursively smoothing and filtering the pressure time series with moving quantiles, applying two window widths and quantiles in succession, with the second filtering the output of the first. This process can be limited to bounds which encompass surface fluctuations. Tags may experience differing levels of noise. By analysing the raw plotted data, we can identify drift and level shifts, and adjust the windows and quantiles accordingly (Luque and Fried, 2011). To exclude surface noise, we set the dive threshold at 1 m (Navarro *et al.*, 2014). We also excluded all dives with dive durations longer than 10 minutes, and descent rates exceeding 3 m/s (Frankish *et al.*, 2021). When reporting summary statistics, we first calculated an overall mean descent rate, as well as a mean that excludes dives <5 m. Surface noise can lead to the overestimation of descent rates, disproportionately affecting shallow dives. Therefore, excluding dives <5 m may provide a more accurate reflection of true descent rates (Rollinson, 2014). Consequently, only dives >5 m were used in the analysis of descent rates.

We investigated the diving behaviour of the three *Procellaria* species by comparing dive depths, durations, and descent rates with permutation tests (Voeten, 2023). Separate models were performed for each diving behaviour, species and sex. Results have not been adjusted for multiple comparisons. Descent rate, maximum depths and dive durations are all gamma distributed. Most White-chinned Petrels were of unknown sex, and therefore sex-specific diving is not tested for. Black Petrel sexing is based on behaviour and morphological observations ('clacking' for female, size of bird, and bill depth), and has not yet been confirmed with genetic analysis. It should thus be noted that these are preliminary analyses and may be subject to changes.

**Table 1.** Summaries of TDR deployments, retrievals and datasets obtained for White-chinned, Black, and Westland Petrels from New Zealand. Totals for each species shown in **bold**.

Species	Location	Year	TDR type (sampling freq.)	No. deployed	No. retrieved	No. with data
White- chinned Petrel	Antipodes	2022	Star-ODDI (2 s)	9	8	6
	Antipodes	2022/23	CEFAS (1 s)	15	11	7
	<b>Total</b>			<b>24</b>	<b>19</b>	<b>13</b>
Black Petrel	Aotea	2023	CEFAS (1 s)	10	9	3
	Aotea	2023/24	CEFAS (1 s)	10	7	6
	Aotea	2024	CEFAS (1 s)	1	1	1
	<b>Total</b>			<b>21</b>	<b>15</b>	<b>10</b>
Westland Petrel	West coast	Jun 2022	Star-ODDI (2 s)	10	9	9
	West coast	Aug 2022	CEFAS (1 – 2 s)	20	18	14
	West coast	2023	CEFAS (1 s)	15	12	9
	<b>Total</b>			<b>45</b>	<b>38</b>	<b>32</b>

## **Northern Hemisphere study on Hawaiian *Phoebastria* albatrosses**

To add to the limited diving ecology data of *Phoebastria* petrels from the Northern WCPO, we studied Laysan and Black-footed and Albatross from Hawai'i, U.S.A.

### ***Data collection***

We deployed archival GPS (i-gotU, USA; Mr. Lee, USA) and custom-built data loggers carrying a barometric pressure sensors and 3-axis accelerometer (AxyAir, TechnoSmart, Italy) on 31 breeding adult Laysan Albatrosses and 32 breeding adult Black-footed at their colonies on Midway Atoll (28.2°N, 177.4°W) in the Papahānaumokuākea Marine National Monument during four field seasons (over the course of 2016-23). Data loggers were attached to feathers on the back of each bird using Tesa tape and all instrument packages were <3% of the body mass of either species. The barometric pressure sensors recorded data at 1 s intervals with a pressure range of 1-2000 mbar and an accuracy of 2.5 bar. Following retrieval, we obtained a dataset from Laysan Albatrosses of 198 sampling days and from Black-footed Albatrosses of 394 sampling days for further analyses.

### ***Data analysis***

We calculated dive depths from the recorded barometric pressure by subtracting the ambient pressure from the recorded pressure and multiplying the result by 0.01 to convert bar to meters (Elliott and Gaston 2009). Ambient pressure was estimated iteratively from a 120 s rolling mean; potential dives were identified and then subsequently omitted from the calculation of ambient pressure and dive depths were recalculated. This process also corrected for surface noise. Dives were classified as any measurements deeper than 0.2 m (20 cm). A series of paired casts with a RBR Concerto CTD (Ottawa, Canada) indicated high correlation between the depths measured by the RBR Concerto and those calculated using the AxyAir dataloggers. This approach allowed us to calculate dive depth, duration, shape, and dive frequency that included dives to depths deeper than 20 cm. It should be noted that these are also preliminary analyses and may be subject to changes.

## **Synthesis of albatross and large petrel diving data relevant to the WCPO**

We conducted a literature review on albatross and petrel diving ecology to place the results from both the New Zealand *Procellaria* study and the Northern Hemisphere *Phoebastria* study into a wider context, evaluate the perceived differences in diving ecology of large petrels and albatrosses between the Southern and Northern WCPO, and ultimately, to provide further information to the review of WCPFC CMM 2018-03. This involved a review of the scientific literature through a Google Scholar search a compilation of all papers describing diving ecology - dive depths and descent rates in particular - for albatrosses and large petrels occurring in the WCPO that are vulnerable to bycatch in pelagic longline fisheries. We only selected studies employing modern biologging devices as these are more reliable than previous methods employing less advanced technologies (e.g., capillary tubes).

This literature review yielded 10 suitable papers covering five albatross species and four large petrel species (Huin and Prince 1997; Hedd *et al.*, 2008; Rayner *et al.*, 2011; Bell 2016; Rollinson *et al.*, 2014, 2016; Kazama *et al.*, 2019; Bentley *et al.*, 2021; Frankish *et al.*, 2021; Guilford *et al.*, 2022). After adding the species from the two studies described above, our Southern Hemisphere dataset consisted of four albatross and five large petrel species, and our Northern Hemisphere dataset consisted of two albatross species and one large petrel species. We then extracted mean dive depths, maximum dive depths, and where available, descent rate from these papers for further analysis and comparison.

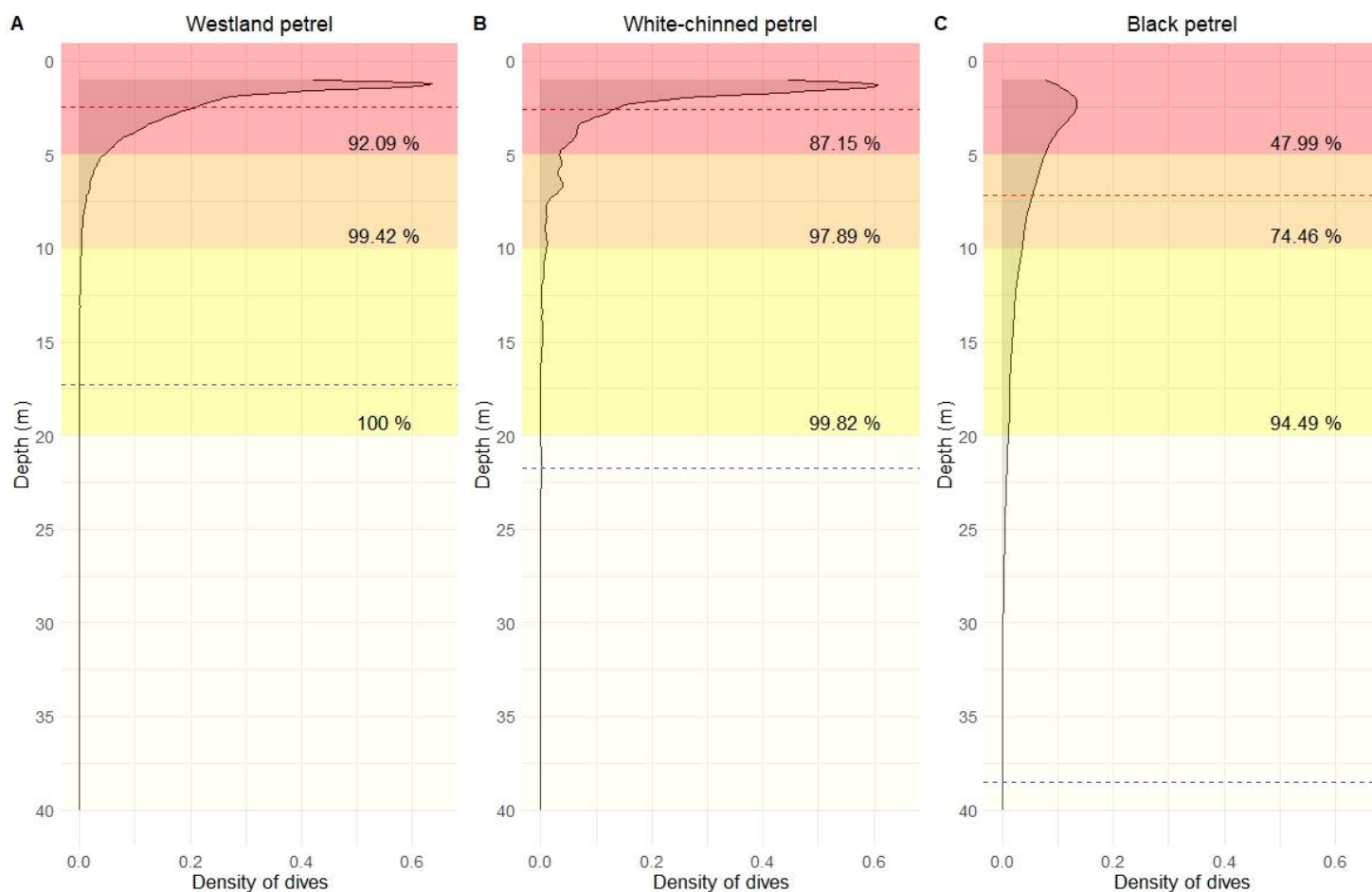
## RESULTS

### Southern Hemisphere study on New Zealand *Procellaria* petrels

Summary statistics of White-chinned, Black, and Westland Petrel diving ecology are presented in Table 2. Most Westland and white-chinned dives were <5 m (92.1% and 87.2% respectively), and almost all dives for these species were <10 m (99.4% and 97.9% respectively) though the dive limits for both birds far exceeded these thresholds, with the maximum depth for Westland at 17.31 m, and at 21.72 m for White-chinned Petrels (Figure 1). In contrast, the minority of Black Petrel dives were <5 m (48.0%), and still only 74.5% were below 10 m (Figure 1). The maximum dive for the Black Petrel was also significantly deeper, at 38.5 m. We found maximum dive depths differed significantly across species, with Black Petrels diving deeper than both Westland ( $\beta = -0.90$ ,  $p < 0.001$ ) and White-chinned Petrels ( $\beta = 0.77$ ,  $p < 0.001$ ; Sup. Mat 1). Westland Petrel dives were significantly shallower than White-chinned Petrels ( $p < 0.001$ ), but the difference was less pronounced ( $\beta = -0.13$ ). Black Petrel dive durations were on average the longest (mean = 17.25 s), but this was only statistically significant when compared to Westland Petrels (mean = 5.23 s;  $\beta = -1.13$ ,  $p < 0.001$ ). Descent rates were greatest in the Westland Petrel at 1.01 m/s compared to both the Black ( $\beta = 1.98$ ,  $p < 0.001$ ) and White-chinned Petrel ( $\beta = 0.21$ ,  $p < 0.001$ ), and no significant difference was found between Black and White-chinned Petrel. Sex-specific diving behaviour was found in both Westland and Black Petrels. In both species, males dived significantly deeper (Westland:  $\beta = 0.1$ ,  $p < 0.001$ ; Black:  $\beta = 0.16$ ,  $p < 0.001$ ). In Black Petrels male descent rates were faster than females ( $\beta = 0.15$ ,  $p < 0.001$ ). No sex-specific dive durations were found.

**Table 2.** Summary statistics of diving ecology for each *Procellaria* species and sex. Note that there is only one sexed female white-chinned in this study. Depth measured in metres; duration measured in seconds; descent rate measured in m/s; dive frequencies per day from first to last recorded dive.

Species		Depth m		Dive duration	Descent rate	Mean descent	Mean dive
		Max	Mean	(s)	excl. dives <5	rate incl. dives	frequency
					m (m/s)	<5 m (m/s)	(n/day)
Westland	Female	12.22	2.21 ± 0.13	4.37 ± 0.37	1.02 ± 0.07	1.61 ± 0.06	6.40 ± 0.63
	Male	17.31	2.42 ± 0.09	5.82 ± 1.00	1.00 ± 0.02	1.47 ± 0.04	8.85 ± 0.92
	<b>All</b>	<b>17.31</b>	<b>2.31 ± 0.10</b>	<b>5.23 ± 1.01</b>	<b>1.01 ± 0.03</b>	<b>1.52 ± 0.04</b>	<b>7.86 ± 0.63</b>
White-chinned	Female	4.43	1.72	3.46	-	1.75	2.17
	Male	21.72	3.68 ± 0.54	8.21 ± 1.92	0.90 ± 0.04	1.53	3.36 ± 0.65
	Unkn.	14.19	2.51 ± 0.29	6.17 ± 0.95	0.80 ± 0.05	1.34 ± 0.14	5.80 ± 1.06
	<b>All</b>	<b>21.72</b>	<b>2.63 ± 0.57</b>	<b>6.59 ± 0.86</b>	<b>0.84 ± 0.04</b>	<b>1.43 ± 0.09</b>	<b>4.77 ± 0.76</b>
Black	Female	25.50	5.78 ± 2.09	20.05 ± 6.82	0.79 ± 0.06	0.86 ± 0.08	9.28 ± 2.50
	Male	38.50	6.82 ± 1.04	18.49 ± 3.35	0.93 ± 0.04	1.15 ± 0.15	13.71 ± 2.89
	Unkn.	29.12	4.29 ± 2.85	10.75 ± 7.92	0.90	1.44 ± 0.36	6.73 ± 5.23
	<b>All</b>	<b>38.50</b>	<b>5.63 ± 0.73</b>	<b>17.25 ± 2.72</b>	<b>0.90 ± 0.04</b>	<b>1.15 ± 0.12</b>	<b>11.43 ± 2.11</b>



**Figure 1.** Density plot of maximum dive depths for A) Westland, B) White-chinned, and C) Black Petrels. Red dotted lines represent species' mean when dives are not grouped by individual, blue dotted lines represent species' maximum depth. Percentages on right-hand side of each graph indicate the following: % of dives 0-5 m (red), % of dives 0-10 m (orange), % of dives 0-20 m (yellow). The density plot illustrates the distribution of the recorded dives, similar to a histogram.

### Northern Hemisphere study on Hawaiian *Phoebastria* albatrosses

Of the equipped individuals, 74% of Laysan Albatrosses and 66% of Black-footed Albatrosses exhibited dives >0.2 m. Both species exhibited dives deeper than 2 m at a similar rate (~2% of recorded dives for both species). Maximum dive depths for both species were similar with 6.02 m for Laysan Albatross and 5.92 m for Black-footed Albatross. All dives >2 m were V-shaped dives. Laysan Albatross exhibited diving behaviour at a considerably higher frequency (2.57 dives >0.2 m per day, compared to 0.39 dives per day in Black-footed Albatross). Further summary statistics can be found in Table 3.

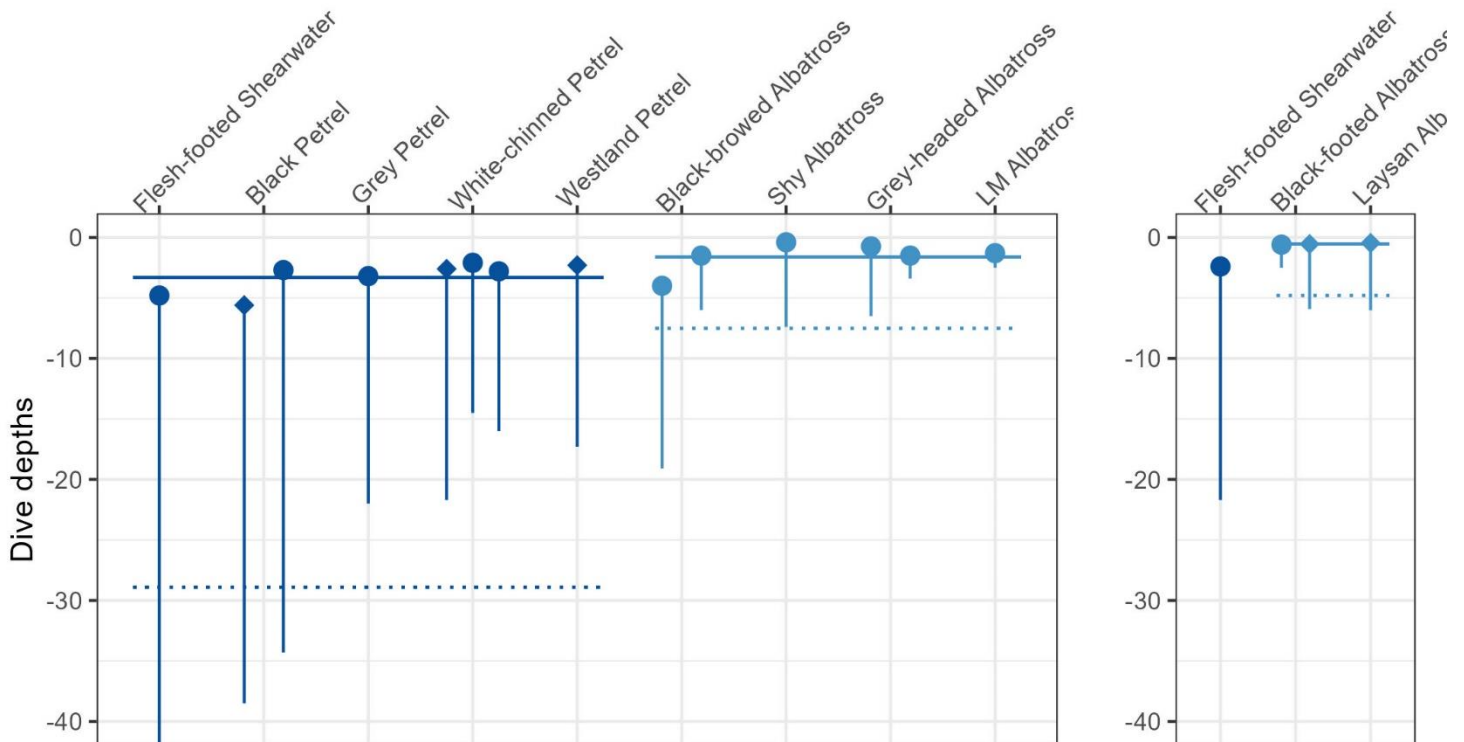
**Table 3.** Summary statistics of diving ecology for two Northern Hemisphere Albatross species. Depth measured in metres; duration measured in seconds; dive frequencies per day from first to last recorded dive.

Species	No. birds with dives	Mean dive depth (m)	Max. dive depth (m)	Mean duration (s)	Max. duration (s)	Dive freq. (n/day)
Black-footed Albatross	21 (65%)	0.55 ± 0.59	5.92	2.9 ± 1.93	18	0.39
Laysan Albatross	23 (74%)	0.46 ± 0.47	6.02	2.5 ± 1.51	24	2.57

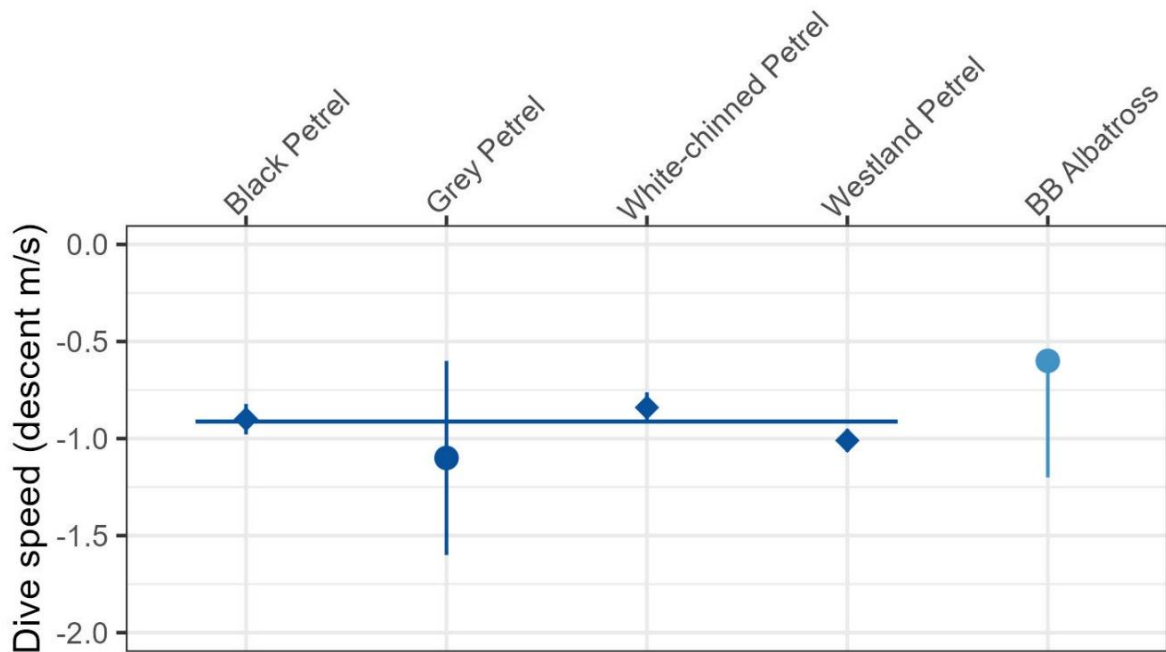


### Synthesis of albatross and large petrel diving data relevant to the WCPO

The data presented in both the *Procellaria* petrel study from New Zealand and the *Phoebastria* albatross study from Hawai'i were considerable additions to the literature available on diving ecology of albatrosses and large petrels (Figure 2). Following these additions, average mean and maximum dive depths for large petrels occurring in the Southern WCPO were 3.26 m, and 28.85 m respectively, while the only study of large petrel dive data from the Northern WCPO (Flesh-footed Shearwater *Puffinus creatopus*) had a reported mean dive depth of 2.4 m and a reported maximum dive depth of 21.7 m. Average mean and maximum dive depths for albatrosses in the Southern WCPO were 1.57 m and 7.48 m, respectively, while average mean and maximum dive depths for albatrosses in the Northern WCPO were 0.54 m and 4.81 m, respectively. Descent rates were only available for species relevant to the Southern WCPO (Figure 3). Average mean descent rate for large petrels in the Southern WCPO was 0.96 m/s and the only reported descent rate for a Southern Hemisphere albatross species (Black-browed Albatross; *Thalassarche melanophris*) was 0.6 m/s. The limited sample size of studies describing diving ecology, particular from species relevant to the Northern WCPO limited any further statistical tests beyond these simple comparisons of summary statistics.



**Figure 2.** Synthesis of dive depths (mean and maxima) of large petrels (dark blue) and albatrosses (light blue) occurring in the Southern (left panel) and Northern WCPO (right panel). Solid lines indicate average of mean dive depths of taxonomic groups and dotted lines indicate average of maximum dive depths. Circles indicate that data from the literature, diamonds indicate novel data presented in this paper.



**Figure 3.** Synthesis of descent rates of large petrels (dark blue) and albatrosses (light blue) occurring in the WCPO. Solid line indicates the average of large petrels. Circles indicate that data from the literature, diamonds indicate novel data presented in this paper.

## DISCUSSION

The results from the three studies compiled here contribute to our understanding of seabird diving behaviour in the Southern WCPO, which can in turn be used to inform the review of WCPFC CMM 2018-03 to ensure that effective mitigation methods are required and applied across the Convention Area where there is bycatch risk to vulnerable seabirds from longline fishing.

### Southern Hemisphere study on New Zealand *Procellaria* petrels

This study found deeper mean and maximum dive depths in Black Petrels than previously recorded (Bell, 2016). In addition, a greater proportion of dives were recorded above the 5 m and 10 m thresholds. These results have relevance to seabird bycatch mitigation methods. Previously, the common perception was that it was necessary to protect hooks (e.g., through combinations of weighted branch lines and tori lines, or the use of hook shielding devices) until 10 m in the Southern Hemisphere to ensure that they are largely out of range of *Procellaria* petrels. However, 25.5% of Black Petrel dives would still be at risk at this depth. Specifically, our results suggest that hooks remain accessible to Black Petrels up to a minimum depth of 20 m, with only 5.5% of dives exceeding this depth (Figure 1). Interestingly, we found male petrels dived deeper than female, which contrasts with Bell's (2016) findings. Further studies with a larger sample size of genetically sexed individuals may be necessary to extract a thorough understanding of sex-specific foraging behaviours in Black Petrels.

Previous studies on Westland Petrels with capillary tubes recorded a maximum depth of 7.6 m (Freeman and Nicholls, 1997). Our results suggest much deeper depths of up to 17.31 m. With the vast majority of dives shallower than 10 metres (99.4%), protecting hooks up until this threshold may be sufficient to substantially reduce bycatch of Westland Petrels. It should be noted that descent rates are particularly fast in Westland Petrels, with an average of 1 m/s in

dives >5 m, so adequate branch line weighting specifications (e.g., ACAP 2023) appear to be an important consideration to prevent bycatch of this species.

Sex-specific foraging behaviours with male Westland Petrels diving significantly deeper than females is another novel insight. Westland petrels have male-biased sexual size dimorphism, which has in other seabird species been linked to sex-specific foraging behaviours (Landers *et al.*, 2011; Gianuca *et al.*, 2017; Poupart and Waugh, 2020). When investigated with GPS and accelerometer deployments, Westland petrel sexes only differed by the influence of oceanic variables on time spent foraging (Poupart and Waugh, 2020). Our findings provide a novel contribution to our understanding of sex-specific foraging behaviours. Sex specific foraging can put sexes at different risks of bycatch (Gianuca *et al.*, 2017; Cortés *et al.*, 2018). Differing mortality rates between sexes can alter sex ratios and decrease the effective population size (Lewison *et al.*, 2012). The potential for sex-specific bycatch risk in Westland petrels emphasizes the need to thoroughly understand the foraging behaviour of these at-risk species and adjust mitigation measures accordingly.

Our study shows similar distributions of white-chinned petrel dive depths to Frankish *et al.*, (2021), though the maximum depth recorded in this study (21.72 m) is several metres deeper than the previous record of 16 m (Rollinson *et al.* 2014). Despite this impressive diving ability, 97.9% of dives remained below 10 m, indicating that this is an appropriate minimum depth to protect hooks to. This study provides preliminary insights into the diving behaviour of three *Procellaria* petrel species vulnerable to bycatch in fisheries. Further studies should explore additional diving behaviour parameters, such as dive frequencies and profiles, and factors influencing behaviour, including the time of day.

#### **Northern Hemisphere study on Hawaiian *Phoebastria* albatrosses**

Our study on Black-footed and Laysan Albatross diving ecology highlighted that both species have the capability to dive beyond 2 m depth, which was the previously assumed maximum dive depth of these species, based on a study by Kazama *et al.* (2019). Our study showed that both species have surprisingly similar diving ecology in terms of diving depth and duration and most notably, both species can dive to depths of ~6 m. It should be noted that both species dive deeper than 2 m depth very rarely (only ~2% of dives), even if Laysan Albatross in general is a more frequent diver. However, as devices were back mounted on these albatrosses, the reach of the bird's bill may extend further and more often beyond the previously perceived maximum depth of 2 m. This consideration is valid for the leg-mounted study on the *Procellaria* petrels as well.

Consequently, our study challenges the perception that hooks in the Northern WCPO only need to be protected (e.g., by combining tori lines and weighted branch lines or hook shielding devices) until they have sunk beyond 2 m depth and as such, this consideration should be taken into account during the review of WCPFC CMM 2018-03.

#### **Synthesis of albatross and large petrel diving data relevant to the WCPO**

We here presented the first synthesis of albatross and petrel diving ecology with particular relevance the WCPO. While this study contributes new insights, dive data is still comparatively sparse, particularly in the Northern Hemisphere. Further study may provide more evidence of deep diving behaviour, as has been the case for the Southern Hemisphere (Guilford *et al.*, 2022). While limited data constrained our ability to provide robust statistical comparisons between the diving ecology of Southern and Northern Hemisphere species, our analyses highlight that diving ecology is more similar between the two Hemispheres than previously

assumed. Specifically, mean and maximum large petrel dive depth was 3.3 m vs. 2.4 m and 28.9 and 21.7 m for Southern and Northern Hemisphere species respectively. Similarly, mean and maximum albatross dive depth was 1.6 m vs. 0.5 m and 7.5 and 4.8 m, respectively. Consequently, these novel findings should be taken into account during the review of CMM 2018-03.

### **Relevance of seabird diving ecology to the review of CMM 2018-03**

Seabird bycatch mitigation methods for pelagic longlines in general are designed to prevent birds from accessing hooks, in particular during the set, when risk of drowning is the greatest. This can be achieved by setting hooks at night, when birds are less active, using tori lines that scare birds away from sinking hooks, and weighting branch lines to ensure that hooks are out of reach of seabirds more quickly (ACAP 2023; Pierre 2023). These three methods all have shortcomings and thus these methods are best used in combination to ensure the best protection of the sinking hooks (ACAP 2023). Alternatively, hook-shielding devices or underwater bait setters can be used, that prevent access to hooks until a certain safe depth is reached (Robertson *et al.*, 2018; Sullivan *et al.*, 2017).

The data presented here has implications for tori lines and weighted branch lines and the specifications thereof and may also be relevant for hook shielding devices and underwater bait setters. Specifically, the aerial extent of tori lines should cover hooks until they have sunk below a depth that birds can usually access, which means that the tori line aerial extent requirements are determined by the sink rates of hooks and the setting speed of the vessel. For example, if a vessel is setting hooks at 7 knots, hooks sinking at 0.3 m/s will reach 10 m depth 120 m behind the vessel, while hooks sinking at 0.5 m/s will reach 10 m depth at 72 m behind the vessel.

Tori line specifications in WCPFC CMM 2018-03 require an aerial extent of 100 m for the Southern Hemisphere. Thus, sink rates at 0.5 m/s would mean that current tori line specifications in the Southern Hemisphere are generally sufficient (depending on the setting speed) to prevent most seabirds from accessing hooks. However, achieving sink rates of 0.5 m/s, would require  $\geq 40$  g weights within 0.5 m of hooks,  $\geq 60$  g within 1 m of hooks, or  $> 80$  g within 2 m of hooks (e.g., Barrington *et al.*, 2016). This would require adjustments of the current WCPFC CMM 2018-03 specifications. The deep-diving ability of Black Petrels and the fast-diving ability of Westland Petrels means that a combination of tori lines and weighted branch lines alone would not be enough to protect these species, and the additional measure of night setting would be needed in the Southern Hemisphere. Finally, in light of the deep-diving ability of Black Petrels, specification of hook-shielding devices and underwater bait setters should consider the safe depths are at which hooks are generally not available to seabirds.

Tori line specifications in WCPFC CMM 2018-03 provide no minimum aerial extent for the Northern Hemisphere. With these specifications, tori lines in the Northern Hemisphere are unlikely to ensure that hooks are out of reach of Northern Hemisphere seabirds under current branch line weighting regimes. Small-vessel tori lines can have aerial extends of 30-40 m only (e.g., Ochi 2022) and thus with the new insights on the diving ability of Northern Hemisphere albatrosses, branch line weighting regimes should also be adjusted in the Northern Hemisphere. A minimum aerial extent of tori lines in the Northern Hemisphere should be set at similar specification to the Southern Hemisphere to ensure adequate protection is provided for up to 6 m at the end of the aerial extent of the tori line.

In conclusion, the insights we have gained on the diving ecology of seabirds in the WPO shows that changes to the current specification of seabird bycatch mitigation options is needed to reduce bycatch to low levels.

## ACKNOWLEDGEMENTS

We thank all the field staff involved with the deployment and retrieval of devices. Special thanks goes to E Bell and S Ray for Black Petrel fieldwork; G Elliott, G Parker, K Rexer-Huber and K Walker for White-chinned Petrel fieldwork, and S Bose, M Charteris, S Bose, K Simister and G Taylor for Westland Petrel fieldwork.

## REFERENCES

- ACAP. (2023). Updated ACAP advice on reducing the bycatch of albatrosses and petrels in WCPFC fisheries. WCPFC-SC19-EB-IP-21.
- Barrington, J.H.S., Robertson, G., Candy, S.G. (2016). Categorising branch line weighting for pelagic longline fishing according to sink rates. ACAP SBWG7 DOC7.
- Bell, E. A. (2016). Diving behaviour of black petrels (*Procellaria parkinsoni*) in New Zealand waters and its relevance to fisheries interaction. *Notornis*, 63(2), 57–65.
- Bentley, L.K., Kato, A., Ropert-Coudert, Y., Manica, A., Phillips, R.A. (2021). Diving behaviour of albatrosses: implications for foraging ecology and bycatch susceptibility. *Marine Biology* 168: 36. <https://link.springer.com/article/10.1007/s00227-021-03841-y>
- Cortés, V., García-Barcelona, S., & González-Solís, J. (2018). Sex- and age-biased mortality of three shearwater species in longline fisheries of the Mediterranean. *Marine Ecology Progress Series*, 588, 229–241. <https://doi.org/10.3354/meps12427>
- Elliott, K.H., Gaston, A.J. (2009) Accuracy of Depth Recorders. *Waterbirds* 32:183–191.
- Frankish, C. K., Manica, A., Navarro, J., & Phillips, R. A. (2021). Movements and diving behaviour of white-chinned petrels: Diurnal variation and implications for bycatch mitigation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 31(7), 1715–1729. <https://doi.org/10.1002/aqc.3573>
- Freeman, A. N. D., & Nicholls, D. G. (1997). Radio- and Satellite-tracking Westland Petrels *Procellaria Westlandica*.
- Gianuca, D., Phillips, R. A., Townley, S., & Votier, S. C. (2017). Global patterns of sex- and age-specific variation in seabird bycatch. *Biological Conservation*, 205, 60–76. <https://doi.org/10.1016/j.biocon.2016.11.028>
- Gilman E., Brothers N., Kobayashi D., Martin S., Cook J., Ray J., Ching G., Woods B. (2003). Performance Assessment of Underwater Setting Chutes, Side Setting, and Blue-Dyed Bait to Minimize Seabird Mortality in Hawaii Pelagic Longline Tuna and Swordfish Fisheries. Final Report. National Audubon Society, Hawaii Longline Association, U.S. National Marine Fisheries Service Pacific Islands Science Center, U.S. Western Pacific Regional Fishery Management Council: Honolulu, HI, USA.
- Gilman, E., Brothers, N., & Kobayashi, D. R. (2005). Principles and approaches to abate seabird by-catch in longline fisheries. *Fish and Fisheries*, 6(1), 35–49. <https://doi.org/10.1111/j.1467-2679.2005.00175.x>
- Guilford, T., Padget, O., Maurice, L., Catry, P. (2022). Unexpected deep diving in an albatross. *Current Biology* 32(1): 26-28. <https://doi.org/10.1016/j.cub.2021.11.036>
- Hedd, A., Gales, R., Brothers, N., Robertson, G. (2008). Diving behaviour of the shy albatross *Diomedea cauta* in Tasmania: Initial findings and dive recorder assessment. *Ibis* 139: 452-460. <https://doi.org/10.1111/j.1474-919X.1997.tb04658.x>

- Huin, N., and Prince, P.A. (1997). Diving behaviour of the grey-headed albatross. *Antarctic Science* 9: 243-249. <https://doi.org/10.1017/S0954102097000321>
- Jimenez, S., Domingo, A., Abreu, M., Brazeiro, A. (2012). Bycatch susceptibility in pelagic longline fisheries: are albatrosses affected by the diving behaviour of medium-sized petrels? *Aquatic Conservation: Marine and Freshwater Ecosystems* 22(4): 436-445. <https://doi.org/10.1002/aqc.2242>
- Kazama, K., Harada, T., Deguchi, T., Suzuki, H., Watanuki, Y. (2019). Foraging behaviour of black-footed albatross *Phoebastria nigripes* rearing chicks on the Ogasawara Islands. *Ornithological Science* 18(1): 27-37. <https://doi.org/10.2326/osj.18.27>
- Landers, T. J., Dennis, T. E., & Hauber, M. E. (2011). Gender Assignment of Westland Petrels (*Procellaria westlandica*) Using Linear Discriminant Function Analysis. *The Wilson Journal of Ornithology*, 123(4), 720–725. <https://doi.org/10.1676/10-141.1>
- Lewison, R., Oro, D., Godley, B., Underhill, L., Bearhop, S., Wilson, R., Ainley, D., Arcos, J., Boersma, P., Borboroglu, P., Boulinier, T., Frederiksen, M., Genovart, M., González-Solís, J., Green, J., Grémillet, D., Hamer, K., Hilton, G., Hyrenbach, K., ... Yorio, P. (2012). Research priorities for seabirds: Improving conservation and management in the 21st century. *Endangered Species Research*, 17(2), 93–121. <https://doi.org/10.3354/esr00419>
- Luque SP (2024). *\_diveMove: Dive Analysis and Calibration\_*. R package version 1.6.2, <https://CRAN.R-project.org/package=diveMove>.
- Luque, S. P., & Fried, R. (2011). Recursive Filtering for Zero Offset Correction of Diving Depth Time Series with GNU R Package *diveMove*. *PLoS ONE*, 6(1), e15850. <https://doi.org/10.1371/journal.pone.0015850>
- Navarro, J., Votier, S. C., & Phillips, R. A. (2014). Diving capabilities of diving petrels. *Polar Biology*, 37(6), 897–901. <https://doi.org/10.1007/s00300-014-1483-0>
- Orben, R. A., O'Connor, A. J., Suryan, R. M., Ozaki, K., Sato, F., & Deguchi, T. (2018). Ontogenetic changes in at-sea distributions of immature short-tailed albatrosses *Phoebastria albatrus*. *Endangered Species Research*, 35, 23–37. <https://doi.org/10.3354/esr00864>
- Phillips, R. A., Gales, R., Baker, G. B., Double, M. C., Favero, M., Quintana, F., Tasker, M. L., Weimerskirch, H., Uhart, M., & Wolfaardt, A. (2016). The conservation status and priorities for albatrosses and large petrels. *Biological Conservation*, 201, 169–183. <https://doi.org/10.1016/j.biocon.2016.06.017>
- Pierre, J. (2023). Mitigation of seabird bycatch in pelagic longline fisheries: best practice measures, evidence, and operational considerations. WCPFC-SC19-EB-IP15.
- Poupart, T. A., Waugh, S. M., Kato, A., & Arnould, J. P. Y. (2020). Foraging niche overlap during chick-rearing in the sexually dimorphic Westland petrel. *Royal Society Open Science*, 7(11), 191511. <https://doi.org/10.1098/rsos.191511>
- R Core Team (2024). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Rayner MJ, Taylor GA, Thompson DR, Torres LG, Sagar PM, Shaffer SA (2011) Migration and diving activity in three non-breeding Flesh-footed shearwaters *Puffinus carneipes*. *Journal of Avian Biology* 42: 266-270. doi.org/10.1111/j.1600-048X.2010.05238.x
- Reid, T. A., Ronconi, R. A., Cuthbert, R. J., & Ryan, P. G. (2014). The summer foraging ranges of adult spectacled petrels *Procellaria conspicillata*. *Antarctic Science*, 26(1), 23–32. <https://doi.org/10.1017/S0954102013000266>
- Richard, Y., Berkenbusch, K., Crawford, E., Tomquist, M., Walker, K., Elliott, G., Tremblay-Boyer, L. (2024). Antipodean Albatross multi-threat risk assessment. WCPFC-SC20-EB-IP26.
- Robertson, G., Ashworth, P., Ashworth, P., Carlyle, I., Jimenez, S., Forselledo, R., Domingo, A., Candy, S.G. (2018). Setting baited hooks by stealth (underwater) can prevent the

- incidental mortality of albatrosses and petrels in pelagic longline fisheries. *Biological Conservation* 225: 134-143. <https://doi.org/10.1016/j.biocon.2018.06.026>
- Rollinson, D. P., Dilley, B. J., & Ryan, P. G. (2014). Diving behaviour of white-chinned petrels and its relevance for mitigating longline bycatch. *Polar Biology*, 37(9), 1301–1308. <https://doi.org/10.1007/s00300-014-1521-y>
- Rollinson, D. P., Dilley, B. J., Davies, D., & Ryan, P. G. (2016). Diving behaviour of Grey Petrels and its relevance for mitigating long-line by-catch. *Emu - Austral Ornithology*, 116(4), 340–349. <https://doi.org/10.1071/MU15032>
- Sullivan, B.J., *et al.* 2017. At-sea trialling of the Hookpod: a ‘one-stop’ mitigation solution for seabird bycatch in pelagic longline fisheries. *Animal Conservation* 21(2): 159-167. <https://doi.org/10.1111/acv.12388>
- Suryan, R. M., Dietrich, K. S., Melvin, E. F., Balogh, G. R., Sato, F., & Ozaki, K. (2007). Migratory routes of short-tailed albatrosses: Use of exclusive economic zones of North Pacific Rim countries and spatial overlap with commercial fisheries in Alaska. *Biological Conservation*, 137(3), 450–460. <https://doi.org/10.1016/j.biocon.2007.03.015>
- Voeten CC (2023). `_permutest`: Permutation Tests for Time Series Data\_. R package version 2.8, [https://CRAN.R-project.org/package=\\_permutest](https://CRAN.R-project.org/package=_permutest).
- Waugh, S. M., & Wilson, K.-J. (2017). Threats and threat status of the Westland Petrel *Procellaria westlandica*. *Marine Ornithology*, 45, 195–203.
- WCPFC. (2018). Conservation and Management Measure 2018-03: Conservation and management measure to mitigate the impact of fishing for highly migratory fish stocks in the Western and Central Pacific Ocean. WCPFC15.



**SUPPLEMENTARY MATERIAL 1.**

**Sup. Mat. Table 1.** Preliminary results from permutation tests with 1000 iterations, comparing dive depths, durations, and descent rates among species. P-values have not been corrected for multiple comparisons. Descent rates exclude dives < 5 m.

<i>Model</i>	<i>Reference</i>	<i>Factor</i>	<i>LRT</i>	<i>beta</i>	<i>t</i>	<i>p - value</i>
<i>Maximum depths ~ Species</i>	Black	(Intercept)	42399.48	1.73	15.97	
		Westland	7198.43	-0.90	-7.18	< 0.001
		White-chinned	455.19	-0.77	-5.55	< 0.001
	Westland	(Intercept)	17566.86	0.83	12.95	
		White-chinned	81.76	0.13	1.18	< 0.001
<i>Dive duration ~ Species</i>	Black	(Intercept)	63431.05	2.76	20.79	
		Westland	2632.60	-1.13	-7.41	< 0.001
		White-chinned	230.59	-0.96	-5.55	0.09
	Westland	(Intercept)	34909.13	1.63	20.96	
		White-chinned	73.32	0.17	1.17	0.11
<i>Descent rate ~ Species</i>	Black	(Intercept)	289.43	-0.12	-2.25	
		Westland	138.84	0.12	1.98	< 0.001
		White-chinned	4.27	-0.09	-1.19	0.06
	Westland	(Intercept)	5.92	0.00	-0.01	
		White-chinned	28.48	-0.21	-3.58	< 0.001



**Sup Mat. Table 2.** Preliminary results from permutation tests with 1000 iterations, comparing dive depths, durations, and descent rates between sexes in Westland and black petrels. White-chinned petrels have been excluded from these analyses due to insufficient sample sizes of sexed individuals. P-values have not been corrected for multiple comparisons. Descent rates exclude dives < 5 m.

<i>Model</i>	<i>Species</i>	<i>Factor</i>	<i>LRT</i>	<i>beta</i>	<i>t</i>	<i>p - value</i>
<i>Maximum depths ~ Sex</i>	Westland	(Intercept)	10974.76	0.76	13.27	
		Male	567.04	0.10	1.51	< 0.001
	Black	(Intercept)	11079.21	1.68	5.50	
		Male	387.92	0.16	0.45	< 0.001
<i>Dive duration ~ Sex</i>	Westland	(Intercept)	20040.99	1.46	19.18	
		Male	1444.89	0.28	3.01	0.72
	Black	(Intercept)	19728.17	2.94	7.32	
		Male	3.14	-0.16	-0.34	0.99
<i>Descent rate ~ Sex</i>	Westland	(Intercept)	0.25	-0.02	-0.40	
		Male	6.93	0.02	0.52	0.41
	Black	(Intercept)	814.11	-0.24	-3.75	
		Male	459.13	0.15	1.98	<0.001