Gender and geographic variation in morphometrics of white-chinned petrels (*Procellaria aequinoctialis*) in New Zealand and their foraging activities as determined from fisheries bycatch

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Abstract Discriminant function analysis (DFA) was used to determine gender and geographic variation in the morphometrics of white-chinned petrels (*Procellaria aequinoctialis*) measured from fisheries bycatch in New Zealand. Samples were divided into 5 clusters based on capture location. A DFA model was created using adult breeding birds presumed to be from the 2 main locations at the Auckland Islands and Antipodes Islands. Geographic variation in head and bill, skull width, culmen, culmen depth at base, culmen width at base, right and left mid-toe and claw, tail, and right and left wing was found between birds presumed to be from the 'Auckland' and 'Antipodes' clusters, with 'Antipodes' birds being generally larger than 'Auckland' birds. Gender variation in head and bill, skull width, culmen, culmen depth at base, culmen width at base, minimum bill depth, right and left mid-toe and claw, right wing, right and left tarsus existed for 'Auckland' birds. Gender variation in head and bill, skull width, culmen, culmen depth at base, culmen width at base, minimum bill depth, right and left mid-toe and claw, and tail existed for 'Antipodes' birds. Birds in the other 3 clusters were classified as originating from the Auckland Islands or Antipodes Islands. The clustering suggested that birds from the Auckland Islands tended to forage mostly north and west, whereas birds from the Antipodes Islands foraged mostly towards the north. There were large overlaps at Puysegur Point and particularly the Chatham Rise of birds from both breeding locations. This study shows the usefulness of bycatch necropsies, and emphasises the need for further studies in geographic variation and sexual dimorphism at all New Zealand breeding locations.

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Keywords white-chinned petrel; fisheries; bycatch; foraging; discriminant function analysis; morphometric; geographic

INTRODUCTION

Sexual size dimorphism has been found in several seabird species, and morphometric measurements can therefore provide useful information for determining gender (Mallory & Forbes 2005; Shealer & Cleary 2007; Einoder *et al.* 2008; Liordos

& Goutner 2008). Discriminant function analysis (DFA) has been widely used to develop models in which the importance of several morphometric measurements is weighed and used to classify birds with unknown gender (Bertellotti *et al.* 2002; Chochi *et al.* 2002; Setiawan *et al.* 2004; Mallory & Forbes 2005). DFA provides an inexpensive, reliable, and readily-available field method (Mallory & Forbes 2005), and has also been used to show geographic

variation in morphometrics, particularly for Procellariiformes (Granadeiro 1993; Guicking *et al.* 2004; Mallory & Forbes 2005).

The white-chinned petrel (*Procellaria aequinoctialis*) is a circumpolar species occurring at mid- and high-latitudes of the Southern Hemisphere (Onley & Scofield 2007; Martin *et al.* 2009). It breeds on various islands in the Southern Ocean, such as Kerguelen, Crozet, and Prince Edward islands in the South Indian Ocean as well as South Georgia and the Falkland Islands in the South Atlantic (Marchant & Higgins 1990; Reid *et al.* 2007). In the South Pacific Ocean around New Zealand, they breed on Campbell, Auckland, and Antipodes islands (Marchant & Higgins 1990; Reid *et al.* 2007). Population trend data are rare (Marchant & Higgins 1990; Barbraud 2008), particularly for New Zealand breeding sites (ACAP 2009). It has been estimated that at least 100,000 white-chinned petrels bred on Disappointment Island (Auckland Islands group) in 1988, 10,000 on Campbell Island in 1985, and 58,725 on the Antipodes Islands in 2011 (BirdLife International 2012). White-chinned petrels (hereafter WCP) are listed as Vulnerable by the IUCN Red List due to recent population declines (BirdLife International 2012).

WCP experience the highest bycatch rate of any seabird in the Southern Ocean (Phillips *et al.* 2006), and they are one of the species most frequently recorded as bycatch within the New Zealand Exclusive Economic Zone (Abraham & Thompson 2012). Previous analyses of WCP measurements from bycatch between 1998 and 2005 had suggested a potential size difference among specimens, perhaps indicating that birds from the Auckland and Antipodes islands are 2 different taxa (Fraser 2005; Fraser *et al.* 2005).

The objectives of this study were: (1) to use morphometric measurements of WCP caught as fisheries bycatch in New Zealand to determine if gender and geographic variation in size exist between the 2 main breeding locations at the Auckland and Antipodes islands, (2) to create a DFA model to determine the source of each bycatch bird (*i.e.*, 'Auckland' or 'Antipodes' islands), and (3) to use the results from the model created in objective (2) to establish potential differences in foraging areas from the 2 main New Zealand breeding locations.

METHODS

Necropsies were undertaken on WCP caught as fisheries bycatch in the New Zealand Exclusive Economic Zone between April 1998 and September 2005, and again from October 2010 to June 2014 as part of a Conservation Services Programme contract for the New Zealand Department of Conservation. Fishing methods included longliners and trawlers, and birds were returned by observers. Necropsies were conducted on 1459 WCP from these 2 periods. Information about capture location and time was returned with each bird. All specimens were frozen and sent to the contractor to be necropsied by various personnel. A previous analysis of bycatch WCP measurements from 1998 to 2005 by Fraser (2005) found that operator-bias in measurements did not influence final results.

Once thawed, the species identity of each specimen was confirmed. Measurements were not part of the Conservation Services Programme contract and were undertaken voluntarily by the contractors. Vernier calipers (± 0.1 mm) and a ruler (± 1 mm) were used to take the following 11 external morphometric measurements (see Fraser 2005 for methods): (1) head and bill, from supraoccipital to the front curve of the bill; (2) skull width, narrowest width of the head behind the eye sockets; (3) culmen, from base of feathers to front curve of the bill; (4) culmen width at base of bill, the width at the base of the bill at the edge of the feathers; (5) culmen depth at base of bill, the depth at the base of the bill at the edge of the feathers; (6) minimum bill depth, narrowest point of bill excluding nostrils; (7) right and left mid-toe and claw, from anterior side of tarsometatarsus to the end of the mid-toe and claw with toes at right angles to the tarsus; (8) right tarsometatarsus, the medial side from middle of midtarsal joint to distal end of tarsometatarsus with foot towards tail; (9) left tarsometatarsus, the lateral side from middle of midtarsal joint to distal end of tarsometatarsus with foot towards tail; (10) tail, from base to tip of longest feather; (11) right and left wing, maximum flattened cord from carpal joint to tip of longest primary. Gender was determined by examining the gonads, and the age class (adult or sub-adult) was established through a combination of gonad size and oviduct condition, brood patch, and moult (see Bartle 2000).

Only adult breeders were used in this study to avoid bias introduced by different sizes, foraging activities, and dispersal between sub-adults and adults. The breeding season was defined to be between September and May, and any birds caught outside of this period were excluded. The final sample size was 1350, of which 1044 were males compared to 306 females.

The selected specimens were mapped and divided into 5 clusters – 'Auckland' Islands (*n* = 120: 96 males, 24 females), 'Antipodes' Islands (*n* = 139: 129 males, 10 females), 'The Snares' (*n* = 271: 187 males, 84 females), 'Puysegur Point' (*n* = 354: 283 males, 71 females), and 'Chatham Rise' (*n* = 418: 316 males, 102 females) – based on capture location (Fig. 1). Specimens that were closest together were grouped into a cluster, and by using clear gaps between groups as boundaries. Any specimens that

Fig. 1. Locations of birds caught as fisheries bycatch per 25 km grid, shown separately for males (top; n = 1044) and females (bottom; n = 306). Shaded areas represent the five main clusters into which all samples were divided for analyses.
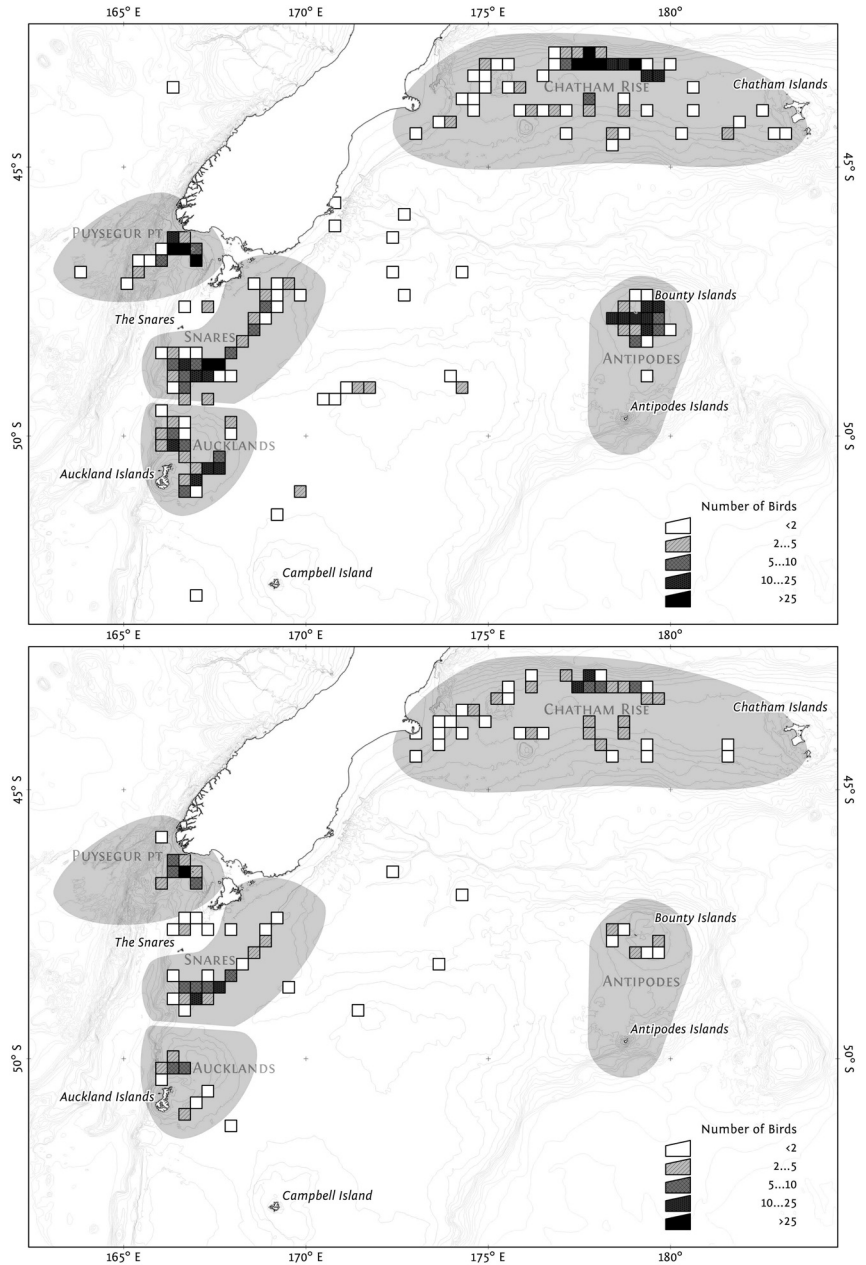
did not fall into a distinct cluster were treated as random points (n = 48: 33 males, 15 females).

Since the aim was to test for gender and geographic variation in morphometrics between birds probably breeding at the 'Auckland' versus 'Antipodes' islands, only the birds falling into these 2 clusters were used for analyses. All analyses were based on the assumption that birds caught in close proximity to the respective islands were breeding there. All birds in the remaining 3 clusters were subsequently

analysed and classified as originating from either breeding location using the DFA developed from the 'Auckland' and 'Antipodes' cluster birds to determine foraging areas and distributions.

Using SPSS version 21 (IBM, Armonk, NY), morphometric data were analysed by dividing the samples into the above-mentioned clusters. Unpaired t-test was conducted to determine significant differences in all measurements between the 'Auckland' and 'Antipodes' islands clusters,

Table 1. Morphometrics of white-chinned petrels caught as fisheries bycatch in New Zealand from 1998 to 2005 and 2010 to 2014 near Auckland and Antipodes islands, with and without gender differentiation. MTC R and L = right and left mid-toe and claw, respectively.

		'Auckland'	'Antipodes'	'Auckland' Male	'Auckland' Female	'Antipodes' Male	'Antipodes' Female
Head and bill	Mean ± SD	114.3 ± 2.6	117.4 ± 2.5	115.0 ± 2.3	111.3 ± 2.5	117.6 ± 2.4	114.5 ± 1.3
	Range (*n*)	107-120 (117)	112-124 (135)	109-120 (94)	105.5-116 (24)	112-124 (125)	113-116 (10)
Skull width	Mean ± SD	36.9 ± 1.9	36.0 ± 1.2	37.4 ± 1.7	34.9 ± 1.5	36.1 ± 1.2	35.0 ± 0.8
	Range (*n*)	32-42.7 (117)	33-40 (139)	33-42.7 (94)	32-36.8 (23)	33-40 (129)	34-36 (10)
Culmen	Mean ± SD	51.8 ± 1.9	54.0 ± 1.6	52.2 ± 1.8	50.2 ± 1.5	54.2 ± 1.6	52.4 ± 1.4
	Range (*n*)	46-56.7 (119)	50-58.8 (131)	47.7-56.7 (95)	46-53.1 (24)	50.6-59.5 (122)	50-54.7 (10)
Culmen depth at base	Mean ± SD	22.4 ± 1.2	21.8 ± 0.9	22.7 ± 1.0	21.2 ± 1.3	21.9 ± 0.8	20.7 ± 0.4
	Range (*n*)	19-24.6 (119)	19-24.5 (139)	20.8-26 (96)	19-24.6 (24)	20-24.5 (129)	20-21 (9)
Culmen width at base	Mean±SD	20.9 ± 1.0	20.4 ± 0.9	21.2 ± 0.7	19.7 ± 1.1	20.4 ± 0.9	19.4 ± 0.5
	Range (*n*)	18.4-22.8 (119)	17-23 (139)	19.3-22.8 (96)	18-22.1 (24)	17-23 (129)	19-20 (10)
Minimum bill depth	Mean ± SD	15.6 ± 0.9	15.8 ± 0.7	15.9 ± 0.8	14.6 ± 0.6	15.9 ± 0.6	14.8 ± 0.6
	Range (*n*)	13.5-17.9 (120)	14-18 (138)	14.1-17.9 (96)	13.5-16 (24)	14-18 (128)	14-15.5 (10)
MTC R	Mean ± SD	85.0 ± 2.7	86.6 ± 2.7	85.5 ± 2.6	83.2 ± 2.5	86.7 ± 2.7	84.5 ± 2.5
	Range (*n*)	78.7-92.8 (117)	80-93 (134)	78.8-92.8 (95)	78.7-88 (22)	80-93 (126)	82-89 (8)
MTC L	Mean ± SD	85.1 ± 2.7	86.5 ± 2.6	85.5 ± 2.7	83.4 ± 2.5	86.6 ± 2.6	83.8 ± 1.1
	Range (*n*)	79.3-93.1 (118)	80-93 (133)	79.3-93.1 (95)	80-88 (23)	80-93 (123)	83-86 (9)
Tarsus right	Mean ± SD	67.0 ± 2.0	67.0 ± 1.6	67.3 ± 1.9	65.5 ± 1.7	67.0 ± 1.7	66.6 ± 1.5
	Range (*n*)	62.5-71.8 (115)	61-70 (138)	62.5-71.8 (94)	63-70 (22)	61-70 (128)	65-69 (10)
Tarsus left	Mean ± SD	66.5 ± 2.2	66.3 ± 1.8	67.0 ± 2.1	64.9 ± 2.1	66.4 ± 1.6	65.8 ± 1.5
	Range (*n*)	61-71.9 (118)	60-70 (139)	62-71.9 (95)	61-69.9 (24)	63-70 (126)	64-68 (10)
Tail	Mean ± SD	124.7 ± 4.0	128.5 ± 4.5	124.0 ± 4.7	125.2 ± 3.5	128.6 ± 4.5	124.5 ± 6.0
	Range (*n*)	116.5-133 (96)	116-139 (137)	112-133 (80)	117.8-130 (20)	115-139 (129)	115-132 (10)
Wing right	Mean ± SD	383.6 ± 8.4	398.3 ± 7.1	384.4 ± 8.4	379.0 ± 7.0	398.4 ± 7.3	395.0 ± 6.1
	Range (*n*)	364-402 (94)	383-414 (132)	364-402 (80)	364-390 (14)	382-414 (124)	385-404 (9)
Wing left	Mean ± SD	383.4 ± 8.3	398.0 ± 7.3	384.1 ± 8.2	380.6 ± 8.2	398.2 ± 7.3	394.3 ± 7.1
	Range (*n*)	365-401 (98)	380-414 (133)	365-401 (80)	368-396 (18)	380-414 (125)	385-404 (9)

irrespective of gender. Unpaired *t*-test was also conducted to determine sexual dimorphism within each cluster. A one-way ANOVA, followed by Bonferroni HSD test, was used to determine significant differences in all measurements between the 2 clusters by including gender as an additional variable.

A cross-validated DFA using a stepwise method was created to explore the differences observed between the 'Auckland' and 'Antipodes' clusters, irrespective of gender (*n* = 259). All remaining data points which did not fall into the 'Auckland' or 'Antipodes' islands clusters were then run through the DFA to determine from which probable

breeding location they originated. Once classified, all points were mapped to show foraging areas and distributions. For each map, coastlines were sourced from the LINZ Data Service and used under the Creative Commons Attribution 3.0 New Zealand license. New Zealand Region Bathymetry was sourced from National Institute of Water and Atmospheric Research, and used under the Creative Commons Attribution 3.0 New Zealand license. The map projection and 25 km grids were created in World Mercator (WGS 84), EPSG: 3395.

RESULTS
Gender and geographic variation in body size
Morphometric measurements are summarised in Table 1. Sample sizes varied due to some missing measurements of parts of specimens. Irrespective of gender, birds in the 'Antipodes' Islands cluster were generally larger than birds in the 'Auckland' Islands cluster. The means of all measurements were significantly different ($P < 0.001$) except for minimum bill depth ($t_{123} = -1.77$, $P = 0.08$), right tarsus ($t_{218} = -0.18$, $P = 0.85$), and left tarsus ($t_{220} = 1.14$, $P = 0.26$).

Males and females in the 'Auckland' Islands cluster were significantly different ($P < 0.05$) in all measurements except for tail ($t_{98} = -1.03$, $P = 0.31$) and left wing ($t_{96} = 1.61$, $P = 0.11$). Males and females in the 'Antipodes' Islands cluster were significantly different ($P < 0.05$) in all measurements except right tarsus ($t_{136} = 0.90$, $P = 0.37$), left tarsus ($t_{137} = 0.85$, $P = 0.40$), right wing ($t_{131} = 1.37$, $P = 0.17$), and left wing ($t_{132} = 1.54$, $P = 0.13$).

Males in the 'Antipodes' Islands cluster were generally larger than males in the 'Auckland' Islands cluster. The means of all measurements were significantly different ($P < 0.01$) except for minimum bill depth ($F_{1,162} = 1.11$, $P = 0.29$), right tarsus ($F_{1,162} = 0.03$, $P = 0.87$), and left tarsus ($F_{1,162} = 0.87$, $P = 0.35$).

Females in the 'Antipodes' Islands cluster were generally larger than females in the 'Auckland' Islands cluster. Only head and bill ($F_{1,13} = 22.73$, $P < 0.001$), culmen ($F_{1,13} = 16.54$, $P = 0.001$), right wing ($F_{1,13} = 15.91$, $P = 0.002$), and left wing ($F_{1,13} = 15.18$, $P = 0.002$) were significantly different.

There were no significant differences ($P > 0.05$) between 'Auckland' Islands males and 'Antipodes' Islands females for head and bill, culmen, right and left mid-toe and claw, right and left tarsus, and tail, indicative of a large overlap in size between large 'Auckland' Islands males and small 'Antipodes' Islands females. Skull width was the only non-significant difference ($P > 0.05$) between 'Auckland' females and 'Antipodes' males. For all gender analyses, it is important to recall the small sample sizes for females for both clusters ($n = 24$ and 10, Auckland and Antipodes, respectively).

Discriminant Function Analysis model
The DFA model was established using a stepwise function. To avoid exaggerated or biased success of the DFA, a jackknife procedure was applied where each bird was classified using a function created from all birds except the one being classified (Bertellotti *et al.* 2002; Shealer & Cleary 2007). The cross-validated success of the model was determined and is shown in Table 2. There was poorer classification success for 'Auckland' Islands birds than 'Antipodes' Islands birds.

Dechaume-Moncharmont *et al.* (2011) stated that caution should be practiced when using DFA models constructed from small sample sizes ($n < 60$) as classification success could be high simply due to chance. Consequently, although sexual dimorphism was found, no DFA models with gender as an additional variable were created due to the small sample size of females.

Applying the model on remaining samples for foraging areas and distribution
Since WCP caught as bycatch had an unknown origin in terms of breeding location, the DFA model was used to classify all remaining birds in 'The Snares', 'Puysegur Point', and 'Chatham Rise' clusters into either 'Auckland' or 'Antipodes' islands birds (Fig. 2). Table 3 shows the classifications. Distinctions between foraging areas from the 2 islands are seen, where 'Auckland' birds tended to predominantly forage in The Snares and Puysegur Point regions whereas birds from the 'Antipodes' Islands tended to forage in the Chatham Rise area. However, there were a large number of birds from the 'Antipodes' Islands in the Puysegur Point region, and 'Auckland' Islands birds on the Chatham Rise.

DISCUSSION
Both gender and geographic variation in size between white-chinned petrels in the 'Auckland' and 'Antipodes' islands clusters were found. Similar results have been shown for other species, such as short-tailed shearwaters (*Puffinus tenuirostris*; Einoder *et al.* 2008), pink-footed shearwaters (*Puffinus creatopus*; Guicking *et al.* 2004), northern fulmars (*Fulmarus glacialis*; Mallory & Forbes 2005), and black terns (*Chlidonias niger*; Shealer & Cleary 2007). The sexual dimorphism determined in our study should be treated as preliminary due to the small sample size of females. Measurements of a larger number of females should be taken at breeding locations to verify the level of sexual dimorphism.

The lower success of classifying 'Auckland' birds when compared to 'Antipodes' birds is likely due to the substantial overlap between large 'Auckland' males and small 'Antipodes' females. Geographic variation in body size could reflect some adaptation
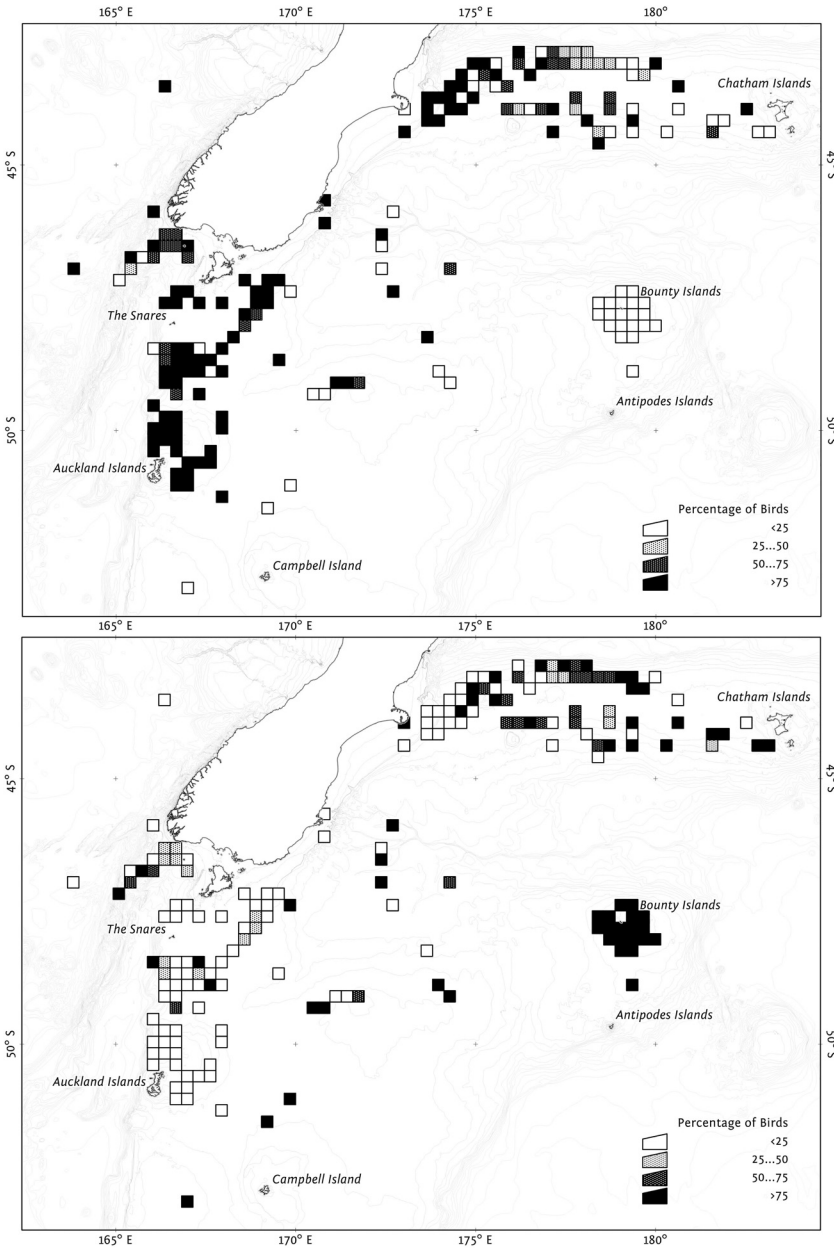
Fig. 2. Predicted foraging patterns and locations per 25 km grid of birds originating from the Auckland Islands (top) or Antipodes Islands (bottom) breeding locations. Predictions were made using birds caught as fisheries bycatch, and were differentiated by a discriminant function analysis model, irrespective of gender.

to different environmental conditions at the breeding sites and potentially different diets and foraging areas (Guicking *et al.* 2004). Bergmann's rule cannot explain this difference as the latitude and temperature of the 2 islands are similar (Ashton 2002). The mapping of bycatch birds caught around The Snares, Puysegur Point, and Chatham Rise following differentiation using the DFA model suggested that there is potential for different diets and foraging areas of birds from the 2 source

locations (Fig. 2). 'Auckland' Islands birds showed a tendency to forage north around The Snares and northwest around Puysegur Point. 'Antipodes' Islands birds tended to forage north to the Chatham Rise. However, there was overlap at Puysegur Point and particularly at the Chatham Rise. This could be indicative of these regions as highly productive areas, thereby attracting a large number of birds. Geolocator tracking from 2008 to 2009 of 17 WCP breeding on the Antipodes Islands showed birds

Table 2. Discriminant function model developed to predict probable breeding location as either Auckland or Antipodes islands, irrespective of gender. Auckland = Auckland Islands, Antipodes = Antipodes Islands. Discriminant variables: SW = skull width, CUL = culmen, CWB = culmen width at base, RightW = right wing. Cutting score = mean of group centroids for Auckland and Antipodes; D > cutting score = Antipodes, D ≤ cutting score = Auckland.

Model	Discriminant function [Cutting Score]	Percent correct classification		
		Auckland	Antipodes	Total
Auckland/Antipodes (no gender)	-0.278SW + 0.538CUL - 0.435CWB + 0.753RightW [-0.321]	84.3	92.7	89.2

foraging north of the Antipodes Islands and east of New Zealand with some individuals concentrated around Puysegur Point, consistent with our findings (Sommer *et al.* 2010). Satellite tracking of 2 *Diomedea* albatross species from Auckland and Antipodes islands showed a similar pattern seen with the WCP (Walker & Elliott 2006). Albatross from Auckland Islands moved north and west, and albatross from Antipodes Islands moved north and east, with overlap between the 2 seen at the Chatham Rise (Walker & Elliott 2006). Tracking should be done on WCP from the Auckland Islands to compare to the findings of our study.

Verification of measurements of WCP at each breeding location needs to be done for the Auckland and Antipodes grouping as the model is based on the assumption that birds were breeding at the island around which they were caught. Tracking of WCP at Crozet Island (Catard *et al.* 2000) and South Georgia (Phillips *et al.* 2006) showed both long and short foraging trips; however, it was assumed in our study that all birds caught close to either island were returning from or departing on a foraging trip. A further limitation is that the Campbell Island colony has been ignored in all analyses due to its assumed small size. Breeding pairs there need to be counted and measurements taken to determine how these birds compare to the other 2 locations.

Males and females were caught in the same areas; however, more males than females were captured (Fig. 1). Catard *et al.* (2000) found male and female WCP from Crozet Island to forage in different areas. Tracking needs to be done at the New Zealand breeding locations to compare results. Different foraging strategies could explain the small number of females caught as bycatch. Ryan & Boix-Hinzen (1999) found male-biased seabird mortality in Patagonian toothfish fisheries. Reasons for this bias are unclear, but females may be outcompeted by larger males at fishing vessels or females avoid vessels more than males and forage elsewhere (Ryan & Boix-Hinzen 1999). The large proportion of males caught could greatly influence demographics of breeding populations.

There is a vast amount of information that can be discovered from bycatch necropsy samples.

A major limitation is that data are only gathered from locations where fishing is occurring and thus does not show other critical feeding areas outside of fishing locations. Bycatch data does, however, identify important overlap areas between foraging birds and fishing, such as the Chatham Rise, where conservation measures are needed. Distinguishing future bycatch birds into 'Auckland' and 'Antipodes' clusters will also aid in determining the potential effect of fisheries on each of the 2 breeding locations. However, because data on colony sizes are limited for New Zealand (ACAP 2009), it would be beneficial to conduct surveys at the breeding locations to determine population size, thereby allowing for calculating proportional impacts of fisheries on each colony. Also, the model was built using breeders, and hence no information was gathered about behavior during the non-breeding season.

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