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Hotspots of seabirds and marine mammals between New Zealand and the Ross Gyre: importance of hydrographic features

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Abstract This article is part of our long-term study on the quantitative at-sea distribution of the marine "upper trophic levels"—seabirds and marine mammals—in polar ecosystems, aiming at quantifying the factors influencing their distribution as well as detecting possible spatial and temporal changes, with special attention to hydrography and to global climate changes. During an expedition of icebreaking RV *Polarstern* in February 2010, along the North–South transect between New Zealand and the Ross Gyre, off the Ross Sea, 3200 seabirds belonging to 22 identified pelagic species were recorded during 338 half-hour transect counts. Four major hotspots were identified. These were in Sub-tropical Water off New Zealand (up to 300 birds per count), and at the main Southern Ocean fronts: the Sub-Antarctic Front (up to 240 per count), the Antarctic Front (up to 150 per count) and the Polar Front (up to 200 per count), representing the vast majority of recorded seabirds. The most numerous species in the three frontal zones were: prions—mainly slender-billed *Pachyptila belcheri*—and Salvin's albatross *Thalassarche* [*cauta*] *salvini.* The eight more abundant species represented 2650 birds, i.e. more than 80% of the total. A random forest clustering method identified four groups of seabird species occupying similar oceanographic niches.

Keywords **seabird at-sea distribution, transect from New Zealand to Antarctica, hydrographic features**

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1 Introduction

At-sea observations of marine "top predators" are essential to understanding the ecological drivers of many species. Although technologies like the Global Positioning System and Geolocator tags are helping to identify environmental parameters that might affect their behaviour, only a limited number of individuals can be targeted. At-sea transects can better identify assemblage areas, and combined with on-board sensors which measure spatially and temporally fine-scale information, we are able to detect the events or features which lead to these accumulations of marine life. This is particularly helpful in remote areas like the Southern Ocean, which have generally poor satellite coverage. The importance of hydrographic features such as water masses and fronts, pack ice and ice edge on seabird distribution was detected decades ago (Pocklington, 1979; Joiris, 1978). The relationship of seabirds and marine mammals to such frontal regions has been previously examined (Force et al., 2015; Ribic et al., 2011; Hyrenbach et al., 2007; Ainley et al., 1998). Important concentrations (hotspots) of marine "top predators" observed in both polar areas were basically associated with such fronts and tended to show a seasonal aspect, being mainly tallied in autumn—a season poorly covered by most marine polar expeditions—and thus seem to

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reflect situations of pre-migratory gatherings following the breeding season (Joiris, 2018a, 2018b, 2018c, 2017, 2015, 2014, 2011; Joiris and D'Hert, 2016; Joiris and Dochy, 2013; Santora et al., 2010). One observation might have corresponded to a pre-nuptial migration: the presence of 18500 chinstrap penguins—representing 90% of all seabirds—in spring 1988 in the Weddell Sea, walking on pack ice toward their breeding sites (Joiris, 1991). In addition, icebergs can show a high productivity from phytoplankton to zooplankton, fish, seabirds and marine mammals (Joiris, 2018a, 2018b, 2011; Smith et al., 2013, 2007; Ruhl et al., 2007).

A general overview of the at-sea distribution of "top predators" in Antarctic seas was produced by Ropert-Coudert et al. (2014), reflecting the importance of biogeographic zones and so stressing the importance of hydrography: pack ice, icebergs and ice edge, water masses and fronts (as recognised from water temperature and salinity data).

Our study aims to perform two tasks: the first is to present this dataset for the public record, and the second is to test the ability of hydrography to compare the oceanographic niches of species along these transects.

2 Materials and methods

In the frame of our long-term study on the distribution at sea of "top predators" —seabirds and marine mammals—in polar ecosystems, our main aims are to study the environmental factors explaining their distribution at sea, as well as to detect possible temporal and spatial evolutions, with special attention to global climatic changes. Seabird and marine mammal quantitative distribution at sea was studied during the first leg of the ANT-XXVI/3 expedition of the icebreaker RV *Polarstern* from Christchurch, New Zealand, on January 31, to the Ross Gyre off the Ross Sea on February 12, 2010. The route of the whole expedition is shown in Figure 1. Transect counts were conducted from the bridge (18 m above sea level) without width limitation during 30-min periods, on a continuous basis as ship operations, light and visibility conditions allowed. No observations were made during night darkness, typically 8–9 h at the beginning of the leg, to 5 h at the end, as well as during sampling stations. When detected, followers were included as far as possible only once per count. More details on our counting method have been described and discussed previously (Joiris, 2018b, 2011; Joiris et al., 2014; Joiris and Falck, 2011). Taking into account the importance of followers and the great heterogeneity in the distribution of top predators, basic data are presented in this article, without correction e.g. for the diving pattern of the animals. Nor are calculations such as density presented.

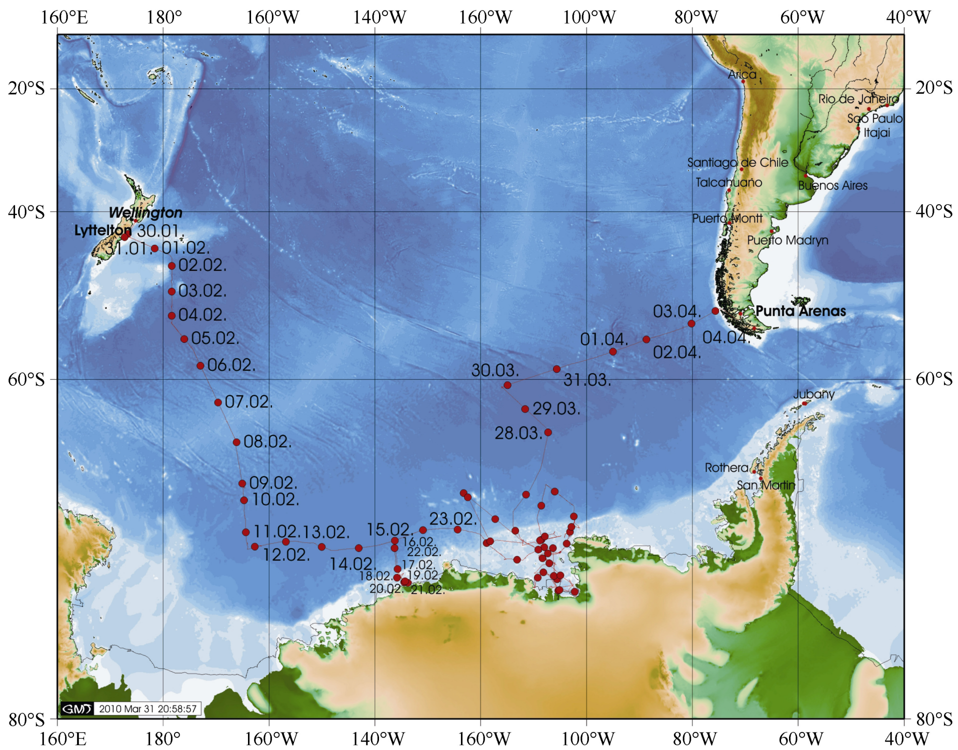

Figure 1 ANTb-XXVI/3 expedition of RV *Polarstern*, February–March 2010: route and noon positions [dd.mm]. Data are from AWI, *Polarstern* ANT-XXVI/3 expedition (Gohl, 2010).

To demonstrate how oceanography can be used to compare geographic niches of species, we opted to use a clustering technique that takes advantage of the non-parametric nature of the random forests algorithm. Random forest is a machine learning algorithm that is based on classification and regression trees (Breiman, 2001; Breiman et al., 1984). It works by building many decision trees and averaging the results (Breiman et al., 1984). Typically, random forest is run in a "supervised" setting, where the goal is to predict to a target variable (Cutler et al., 2007). In our case, we input data to the random forest algorithm without a target to run it in an "unsupervised" setting, where the algorithm looks for differences between data rows (Shi and Horvath, 2006). This can be perceived as a technique similar to principle component analysis but based on regression trees instead of eigenvalues. For our data, we associated all geo-referenced occurrence records with bathymetry as obtained from General Bathymetric Cart of the Oceans (GEBCO; Becker et al., 2009), sea surface temperature and salinity as measured from the ship's on-board systems, and distances to the polar, Antarctic and sub-Antarctic fronts. We then ran the environmental data through the random forest clustering algorithm to determine which species were most similar with regards to their oceanographic niches. The algorithm assigned two scaling factors (representative of how different a data row is from others) to every occurrence record. We took the mean of each scaling factor for each species to assign it a location on the two-dimensional plane which was used to show which species were most similar oceanographically.

3 Results

During the North–South transect of the expedition between Christchurch and the north-eastern corner of the Ross Sea (Ross Gyre), 3200 seabirds belonging to 27 identified species were tallied (including coastal ones off New Zealand) during 338 counts, i.e. a mean value of 11 per count (Table 1). The transect crossed water masses and the main fronts, from north to south were the Sub-Antarctic Front at 48°S, the Antarctic Front at 56°S and the Polar Front at 61°S, the first ones corresponding to the Subtropical Front (STF) and the Subantarctic Front (SAF) respectively in Orsi et al. (1995) (Figure 2). The influence of hydrography was obvious, as reflected by the distribution of the sum of all birds, high concentrations being noted in Sub-tropical Water off New Zealand—where some of the most diverse assemblages of marine birds can be found (Karpouzi et al., 2007) —as well as at the fronts (Figure 3). The most numerous species were 800 prions, mainly slender-billed prions *Pachyptila belcheri* when close enough to be identified, in 14 successive counts at the Polar Front (of which 280 in three counts), 470 sooty shearwaters *Ardenna griseus* dispersed in Sub-tropical Water with a maximum of 65 in one count and 93 in three successive counts, 390 Salvin's albatrosses *Thalassarche* [*cauta*] *salvini* in 27 counts in Sub-tropical Water (of which 35 in one count), 270 white-faced petrels *Pelagodroma marina*, 180 royal albatrosses *Diomedea* [*epomorphora*] dispersed is Sub-tropical water with a maximum of 14 in one count, 150 Cape petrels *Daption capense* in 20 counts, mainly in Sub-tropical Water (of which 48 in three counts). They belonged to the sub-species *D. c. austral.* Close to the Antarctic Front they belonged to *D. c. capense,* in low numbers. 136 wandering albatrosses *Diomedea* [*exulans*] were dispersed in Sub-tropical Water, and 51 black-browed albatross *Thalassarche* [*melanophris*] *melanophris* dispersed from the Polar Front into Sub-Antarctic Water (Figure 4). Together the three most abundant species represented 1650 birds, 50% of the total, and the eight most abundant ones 2647 birds, 80% of the total.

Table 1 "Top predators" —seabirds and marine mammals—recorded during *Polarstern* expedition ANT-XXVI/3, from Christchurch, New Zealand, 31 January to the Ross Gyre, 12 February, 2010. *n*=number of 30 min transect counts; *SST*=mean sub-surface temperature (℃); *N*=total number; mean per count (> 0.01)

	Zone* >	All		STW		SAF		SAW		ANT F		ANT W		
	n >	338		31		20		141		21		125		
	SST/℃ >	-		14.46		15.75		9.50		1.67		−0.24		
	Salinity >	-		34.37		34.26		34.05		33.52		33.67		
	Depth/m >			775		3045		4819		2922		3868		
Species	Species	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	Remark
Adélie penguin	*Pygoscelis adeliae*	44	0.12	0		0		0		0		44	0.35	Pack ice
Wandering albatross	*Diomedea* [*exulans*]	133	0.38	10	0.32	11	0.55	111	0.79	1	0.05	0		
Royal albatross (N & S)	*Diomedea* [*epomophora*]	183	0.57	90	2.9	23	1.15	65	0.46	5	0.24	0		
Black-browed albatross	*Thalassarche* [*melanophris*] *melanophris*	51	0.14	1	0.03	0		26	0.18	4	0.19	0		
Salvin's albatross	*Thalassarche* [*cauta*] *salvini*	392	1.22	338	10.9	27	1.35	27	0.19	0		0		
Light-mantled albatross	*Phoebetria palpebrata*	24	0.07	0		0		19	0.13	3	0.14	2	-	
Northern giant petrel	*Macronectes halli*	24	0.07	9	0.29	1	-	0		2	-	12	0.016	
Southern fulmar	*Fulmarus glacialoides*	22	0.06	0		0		1	-	0		21	0.17	
Antarctic petrel	*Thalassoica antarctica*	21	0.06	0		0		0		0		21	0.17	

Continued

	Zone* >	All		STW		SAF		SAW		ANTF		ANTW		
	n >	338		31		20		141		21		125		
	SST/℃ >	-		14.46		15.75		9.50		1.67		−0.24		
	Salinity >	-		34.37		34.26		34.05		33.52		33.67		
	Depth/m >			775		3045		4819		2922		3868		
Species	Species	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean	Remark
Snow petrel	*Pagodroma nivea*	25	0.07	0		0		0		0		25	0.20	
Cape petrel	*Daption capense*	152	0.45	120	3.87	1	0.05	25	0.18	0		6	0.048	
White-headed petrel	*Pterodroma lessonii*	3	0.01	0		0		0		0		3	0.024	
Soft-plumaged petrel	*Pterodroma mollis*	222	0.63	0		0		217	1.54	5	0.24	0		
Mottled petrel	*Pterodroma inexpectata*	28	0.08	0		0		1	-	2	-	25	0.20	
Blue petrel/prion	*Halobaena/Pachyptila sp.*	10	0.04	5	0.10	1		3	0.021	0		1	-	
Prion sp.	*Pachyptila sp.*	28	0.09	2	0.06	0		18	0.13	8	0.38	0		
Slender-billed prion	*Pachyptila belcheri*	789	2.23	0		0		0		663	31.6	126	1	
Parkinson petrel	*Procellaria parkinsoni*	41	0.12	0		0		41	0.29	0		0		
White-chinned petrel	*Procellaria aequinoctialis*	171	0.57	6	0.19	2	0.10	160	1.13	1	-	2	0.016	
Hutton shearwater	*Ardenna huttoni*	5	-	5	0.16	0		0		0		0		+ 391 off New Zealnd, out of effort
Buller' shearwater	*Ardenna bulleri*	21	0.17	6	0.19	7	0.35	8	0.057	0		0		
Sooty shearwater	*Ardenna griseus*	469	1.37	171	5.52	131	6.55	146	1.04	16	0.76	5	0.040	
Shearwater sp.	*Puffinus/ Ardenna sp.*	6	0.02	0		0		6	0.043	0		0		
Grey-backed storm-petrel	*Oceanites nereis*	7	0.02	0		6	0.3	1	0.007	0		0		
White-bellied storm-petrel	*Fregetta grallaria*	1	-	0		0		1	0.007	0		0		
Black-bellied storm-petrel	*Fregatta tropica*	5	-	1	0.03	0		4	0.028	0		0		
White-faced storm-petrel	*Pelagodroma marina*	269	0.76	228	7.35	38	1.9	3	0.021	0		0		
Storm-petrel sp.	*Oceanitidae sp.*	55	0.16	0		41	2.05	13	0.090	1	0.048	0		
Brown skua	*Catharacta* [*skua*] *antarctica*	2	-	0		1	0.05	1	-	0		0		
Kelp gull	*Larus dominicanus*	3	0.06	3	0.10	0		0		0		0		Coastal
Σ birds		**3186**	10.82	995	32.1	290	14.5	897	6.36	711	33.86	293	2.34	
Number of identified bird species		27												
New-Zealand fur seal	*Arctocephalus forsteri*	5	-	3	0.10	1	0.05	1	0.07	0		0		
New-Zealand sea lion	*Neuphoca cinerea*	1	-	1	0.03	0		0		0		0		
Leopard seal	*Hydrurga leptonix*	4	-	0		0		0		0		4	0.032	
Crabeater seal	*Lobodon carcinophaga*	35	0.10	0		0		0		0		35	0.28	Pack ice
Pinniped sp.	*Pinnipedia sp.*	1	-											
Σ pinnipeds		**45**	0.13	4	0.13	1	0.05	1	0.007	0		39	0.31	
Hector's dolphin	*Cephalorhynchus hectori*	0												12 off New Zealnd, out of effort
Minke whale	*Balaenoptera bonaerensis*	1	-	0		0		0		0		1	0.01	Pack ice
Blue whale	*Balaenoptera musculus*	2	-	0		0		0		0		2	0.016	
Fin whale	*Balaenoptera physalus*	7	0.02	0		0		0		0		7	0.056	
Humpback whale	*Megaptera novaeangliae*	17	0.05	0		0		0		8	0.38	9	0.072	
Σ cetaceans		**29**	**0.05**	2	0.06	0		0		8	0.38	19	0.152	

Notes: * STW: sub-tropical water; SAF: sub-Antarctic front; SAW: sub-Antarctic water; ANTF: Antarctic front + polar front; ANTW: Antarctic water/Ross Gyre.

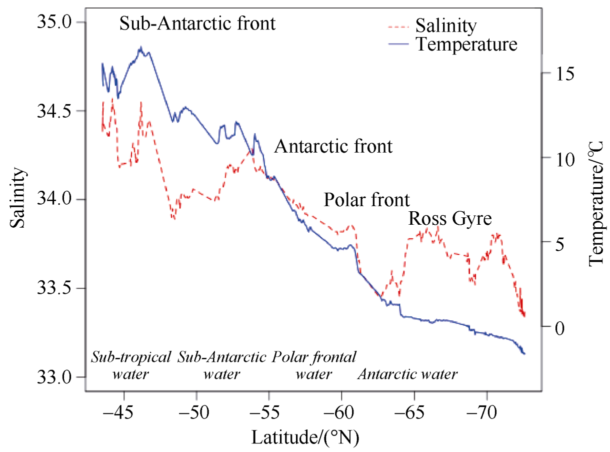

Figure 2 Salinity and water temperature *SST* data recorded on board *Polarstern* at 10 m depth: main water masses (italics, on top) and fronts along the North-South transect between New Zealand and the Ross Gyre. Data are from AWI, *Polarstern* expeditions (Gohl, 2010).

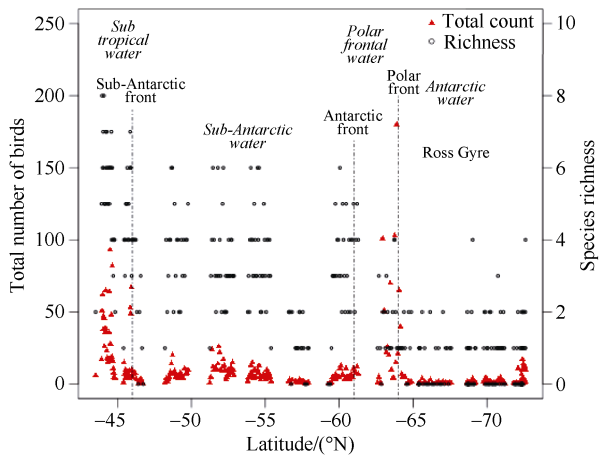

Figure 3 Latitudinal distribution of the most numerous seabird species noted along the North–South transect between New Zealand and the Ross Gyre, main water masses and fronts (see Figure 2): total number of seabirds per count, left scale, dotted lines, and species richness, right scale. This scale is displayed as a loess curve for aesthetic purposes to account for the fact that certain counts had a species richness of zero.

Crabeater seals *Lobodon carcinophaga* were represented by 35 individuals (of which 14 were in one count) in the Ross Gyre and cetaceans by 12 coastal Hector's dolphins *Cephalorhynchus hectori* (out of formal counting periods), and 17 humpback whales *Megaptera novaeangliae*, dispersed off New Zealand and in Sub-tropical Water.

We were only able to perform the clustering analysis for seabirds as there were not enough marine mammal records on this cruise. Also, due to lack of observations, we had to remove blue petrel *Halobaena caerulea*, white-headed petrel *Pterodroma lessonii*, and white-bellied storm-petrel *Fregetta grallaria* from the analysis. Of the seabird species surveyed, 10 seemed to fall into unique oceanographic niches: soft-plumaged petrel *Pterodroma mollis*, white-chinned petrel *Procellaria aequinoctialis*, black-browed albatross *Thalassarche melanophris*, black-bellied storm-petrel *Fregetta tropica*, wandering albatross, sooty shearwater, Antarctic skua *Catharacta maccormicki*, royal albatross, grey-backed storm-petrel *Garrodia nereis* and white-faced storm-petrel *Pelagodroma marina*. All other species fell into four close groupings. Group 1 (Polar Frontal birds; PFb) consisted of slender-billed prion, and mottled petrel *Pterodroma inexpectata* and were found in waters around 3000 m deep, generally around 130 km from the Polar Front. Group 2 (Sub-Antarctic Water birds; SAWb) consisted of light-mantled sooty albatross *Phoebetria palpebrata*, northern giant petrel *Macronectes halli*, and southern fulmar *Fulmarus glacialoides* and were found between the Polar and Sub-Antarctic fronts in cool waters around −0.53℃. Group 3 (Polar birds; Pb) consisted of snow petrel *Pagodroma nivea*, Antarctic petrel *Thalassoica Antarctica*, and Adélie penguin *Pygoscelis adeliae* and were found in waters with temperatures around −1.4℃, approximately 1000 km south of the Polar Front. Group 4 (New Zealand birds; NZb) consisted of Buller's shearwater *Ardenna bulleri*, Salvin's albatross *Thalassarche* [*cauta*] *salvini*, Cape petrel, Hutton's shearwater *Ardenna huttoni*, and kelp gull *Larus dominicanus* and were found primarily off the coast of New Zealand in shallow, warmer waters (Figure 5, Table 2).

4 Discussion

The most striking aspect of the distribution of the "top predators"—mainly seabirds in this case—is its strong dependence on hydrographic features: the Sub-tropical Water on the one hand, and the three main Southern Ocean fronts on the other. The consequence is the important heterogeneity of the distribution, making the "usual" calculations of population densities as a mean value with standard deviation very questionable. The same conclusion applies to other hotspots recorded in both polar areas, in respect to seabirds, cetaceans and seals (see introduction).

The link between very high concentrations and low species diversity seems to reflect both a low biodiversity and a high biological productivity, in Sub-tropical water as well as at the Sub-Antarctic and Polar Fronts.

The method used to examine oceanographic niches of the seabirds did a reasonable job at putting species together into similar groups. For example, Antarctic petrel, snow petrel and Adélie penguin all are generally found below the Polar Front in colder waters. Nicol et al. (2000) describe the southern boundary of the Antarctic current as an important biogeographical boundary, and these three species all occur below this front. Similarly, the birds from group 1 (slender-billed prion and mottled petrel) were correctly classified as occurring in a similar habitat (near to the Polar

Front, PFb). However, the drawback of this method is that we use only data from one ship transect and there are inherent biases that come from seasonality or even weather. The best use of this method in the future would be to combine data from many transects, or sources like the Global Biodiversity Information Facility (GBIF, 2017). Furthermore, a larger suite of oceanographic or ecological factors could be included (e.g. diet or nesting behaviour) to better identify similar species. One example to demonstrate this issue regards the cape petrel, which is generally widely distributed from New Zealand waters down into sub-Antarctic waters. However, on this particular transect, not many cape petrels were seen in the sub-Antarctic waters, and therefore the algorithm identified the cape petrel as a species occupying a similar niche to other species found almost entirely off the coast of New Zealand.

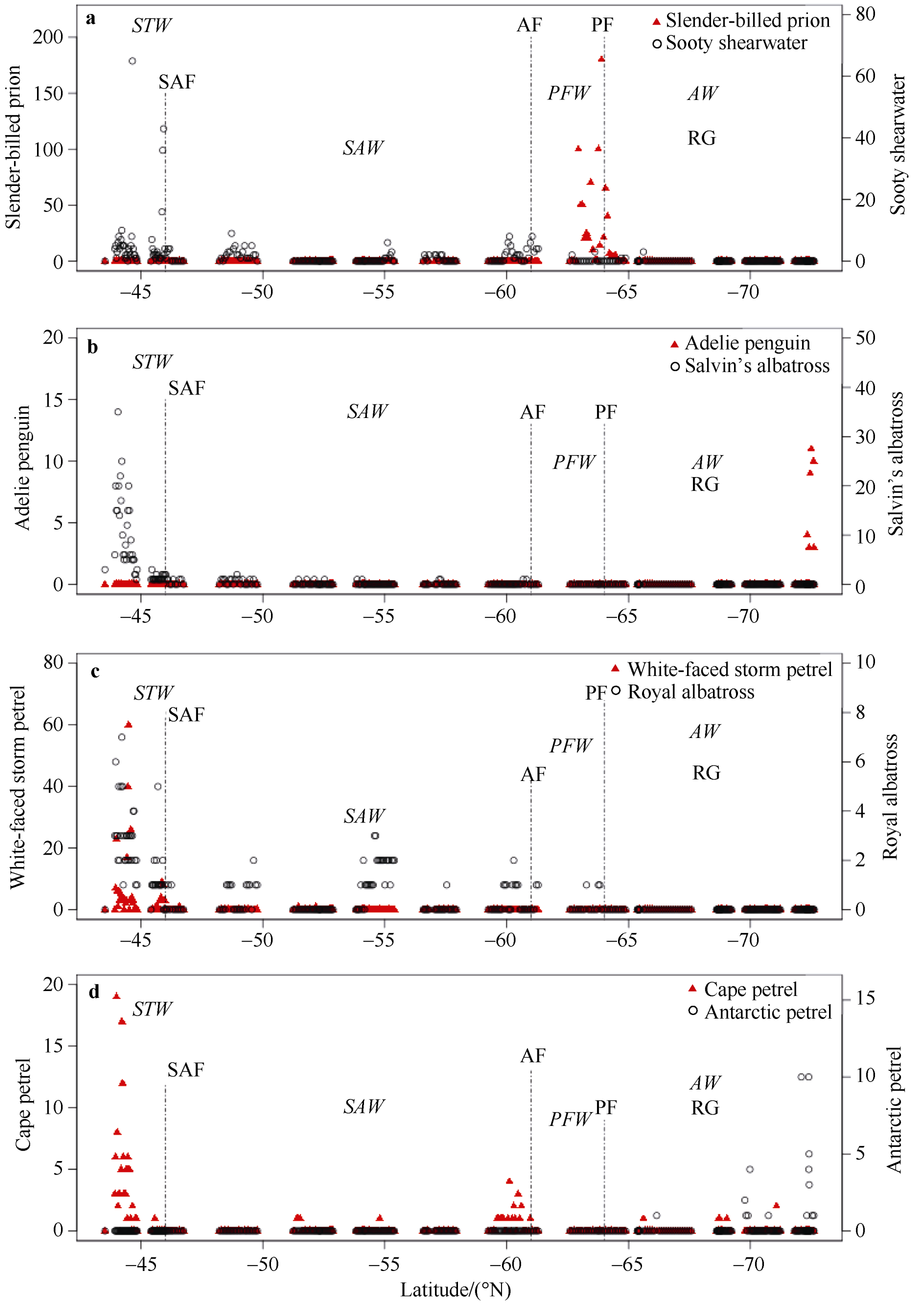

Figure 4 Latitudinal distribution of the eight most numerous seabird species noted along the North–South transect between New Zealand and the Ross Gyre, main water masses and fronts (see Figure 2): **a**, Slender-billed prion *Pachyptila belcheri* and sooty shearwater *Ardenna griseus*; **b**, Adélie penguin *Pygoscelis adeliae* and Salvin's albatross *Thalassarche* [*cauta*] *salvini*; **c**, White-faced petrel *Pelagodroma marina* and royal albatross *Diomedea* [*epomophora*]; **d**, Cape petrel *Daption capense austral* and *D. c. capense* and Antarctic petrel *Thalassoica Antarctica* (see the legend of Figure 3).

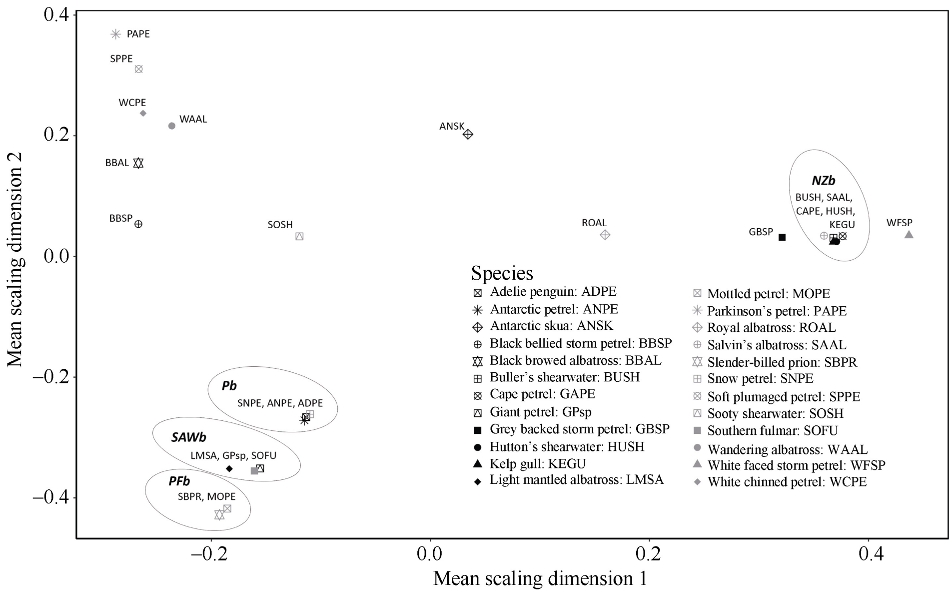

Figure 5 Mean scaling dimensions of each species as determined by the random forests algorithm showing similarities between oceanographic niches of species along the North–South transect between New Zealand and the Ross Gyre (see the legend of Figure 3).

Table 2 Median values of oceanographic variables for the groups identified by the random forest clustering algorithm

	Group	Water temperature (SST)/℃	Salinity	Distance to SAF/km	Distance to AF/km	Distance to PF/km	Depth/m
1	Polar Front birds (PFb)	0.57	33.60	1792	469	135	2918
2	Sub-Antarctic Water birds (SAWb)	−0.23	33.71	2305	1166	814	4070
3	Polar birds (Pb)	−1.41	33.38	2686	1393	1023	4158
4	New Zealand birds (NZb)	14.54	34.3	217	1810	2095	2518

Notes : SAF: Sub-Antarctic Front; AF: Antarctic Front; PF: Polar Front; see Figure 3.

Other clustering analyses performed on data for the Austral autumn has shown similar clusters to our Pb group, where birds identified in this cluster were associated with pack ice (Ainley et al., 1984). Other work in this region has emphasized the importance of environmental parameters such as sea surface temperature for separating species assemblages (Ribic and Ainley, 1989; Ainley et al., 1984, 1983). Our work not only corroborates previous work, but the extensive census work in this region and elsewhere justifies our use of the covarianes for clustering (Ribic and Ainley, 1989).

The dataset we present here not only shows some of the hotspots of marine biodiversity in relation to hydrographic features, but also demonstrates the use of a method for quantifying and easily comparing the oceanographic niches of species in a non-parametric setting.

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