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Seabird distribution on the Humboldt Current in northern Chile in relation to hydrography, productivity, and fisheries

Tanja Weichler, Stefan Garthe, Guillermo Luna-Jorquera, and Julio Moraga

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Factors affecting seabird distribution in the Humboldt Current upwelling system in northern Chile were studied in January 1999 using ship transect counts. Of 24 species recorded, the Peruvian booby (*Sula variegata*), the kelp gull (*Larus dominicanus*) and the Humboldt penguin (*Spheniscus humboldti*) were the most abundant. Species composition varied among different areas of the system and distribution patterns differed substantially among eight of the more abundant species. Most species showed links to variation in environmental factors (trawler distribution, SST and chlorophyll concentration). Principal component analysis identified a feeding-flock factor as the most important one for explaining observed distribution patterns. One-third of all birds recorded were associated in feeding flocks and 3% of all individuals were directly attending fishing vessels.

Keywords: Chile, distribution, feeding flock, fisheries, hydrography, seabirds, upwelling.

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T. Weichler and S. Garthe: Forschungs- und Technologiezentrum Westküste, Hafentörn, D-25761 Büsum, Germany. G. Luna-Jorquera, and J. Moraga: Departamento de Bioloía Marina, Universidad Católica del Norte, Larrondo 1281, Coquimbo, Chile. Correspondence to T. Weichler; fax: +49 4834 604 199; e-mail: weichler@ftz-west.uni-kiel.de.

Introduction

The upwelling system of the Humboldt Current on the west coast of South America is one of the most productive marine ecosystems of the world and supports large stocks of fish, seabirds and marine mammals (Arntz and Fahrbach, 1991). Well-known seabirds of the area are the so-called guano birds: the guanay cormorant, Peruvian booby and Chilean pelican (see Table 1 for scientific bird names). They breed along the coast and on adjacent islands. All three species are endemic to the Humboldt Current (del Hoyo *et al.*, 1992). Their principal prey are pelagic, schooling fishes, chiefly anchovies (*Engraulis ringens*) and sardines (*Sardinops sagax*; Arntz and Fahrbach, 1991). Other endemic seabird species are the Humboldt penguin, Peruvian diving-petrel, grey gull and Inca tern.

The Humboldt Current area is characterized by a strong periodic but irregular climate variation, the El Niño Southern Oscillation (ENSO). In extreme cases, warm surface water forces the schooling fishes to move to greater depths and/or areas farther away from the coast where nutrients are consistently available. Often, these species are then only available in sufficient quantity outside the foraging ranges of incubating and chick-rearing seabirds (Arntz and Fahrbach, 1991). Food availability to seabirds is affected also by another "environmental" variable, the commercial fishery. Especially the anchovy fishery has been intensive over many decades, with landings in 1999 amounting to approximately 8 and 2 million t for Peru (Ministerio de Pesquería de Peru, 2000) and Chile (SERNAPESCA, 1999), respectively.

The distributions of seabirds at sea in relation to hydrography, fisheries and other factors have been investigated in many areas of the world over the past two decades. However, relatively few studies have been conducted around South America. Comprehensive quantitative data have been presented for Pacific equatorial waters by Ribic *et al.* (1997), for the Panama Bight by Spear and Ainley (1999), and for the Beagle Channel in southern Argentina by Raya Rey and Schiavini (2000). For Chilean waters, only classic, qualitative studies are available so far (Murphy, 1936; Jehl, 1973).

To examine how the endemic as well as other seabird species utilize the rich waters of the Humboldt Current, we studied their distribution and abundance in northern Chile during the breeding season in relation to environmental factors such as hydrography and fishing activity.

Materials and methods

Eight cruises on the RV "Stella Maris II" (Universidad Católica del Norte, Coquimbo) were carried out in the

Table 1. Species recorded in transect counts in order of abundance (+: only seen outside transects; scientific names follow Clements, 2000).

Species	N	%
Peruvian booby (*Sula variegata*)	1287	36.1
Humboldt penguin (*Spheniscus humboldti*)	617	17.3
Kelp gull (*Larus dominicanus*)	424	11.9
White-chinned petrel (*Procellaria aequinoctialis*)	287	8.0
Franklin's gull (*Larus pipixcan*)	204	5.7
Buller's albatross (*Thalassarche bulleri*)	142	4.0
Peruvian diving-petrel (*Pelecanoides garnotii*)	130	3.6
Grey gull (*Larus modestus*)	119	3.3
Antarctic prion (*Pachyptila desolata*)	79	2.2
Juan-Fernandez petrel (*Pterodroma externa*)	56	1.6
Guanay cormorant (*Phalacrocorax bougainvillii*)	54	1.5
Wilson's storm-petrel (*Oceanites oceanicus*)	27	0.8
Chilean pelican (*Pelecanus thagus*)	17	0.5
Inca tern (*Larosterna inca*)	11	0.3
Pink-footed shearwater (*Puffinus creatopus*)	10	0.3
Red-legged cormorant (*Phalacrocorax gaimardi*)	6	0.2
Neotropical cormorant (*Phalacrocorax brasilianus*)	6	0.2
Sooty shearwater (*Puffinus griseus*)	3	0.1
"Comic tern" (*Sterna* sp.)	3	0.1
Arctic skua (*Stercorarius parasiticus*)	2	0.1
Skua sp.	1	0.03
Kermadec petrel (*Pterodroma neglecta*)	1	0.03
Antarctic giant petrel (*Macronectes giganteus*)	+	–
Chilean skua (*Catharacta chilensis*)	+	–
Grey phalarope (*Phalaropus fulicarius*)	+	–

Humboldt Current upwelling system of northern Chile between 29°08′30″S and 30°11′S ("Coquimbo area"; Figure 1) between 12 and 29 January 1999. Seabird distribution was studied using transect counts following the method described by Tasker *et al.* (1984) and Webb and Durinck (1992). All seabirds on the water surface up to 300 m from the ship's track were counted directly while flying birds were counted using the "snapshot" method. In principle, bird records were summed over 10 min intervals (Tasker *et al.*, 1984), but intervals often deviated from the norm because of arrival at stations or changes in vessel course. In addition to their mere numbers, typical behaviour such as attending fishing trawlers or being involved in a feeding flock was recorded too. Hydrographic parameters (temperature, salinity and sometimes also chlorophyll) were measured at 51 stations at depths of 10, 20, 30 and 50 m on the same cruises (Figure 1b). During counting, all trawlers within a radius of 5 km were recorded to analyse whether seabird distribution was influenced by their presence by providing a direct food resource in the form of discards at sea. Such effects might be more widespread than suggested by those birds directly attending fishing vessels. Transects extended up to 53 km from the coast covering a total area of 470 km^2 within the 300 m band. To relate seabird densities to environmental parameters, a principal component analysis (PCA) was carried out based on 46 sections of the cruise tracks. Each section comprised a hydrographic

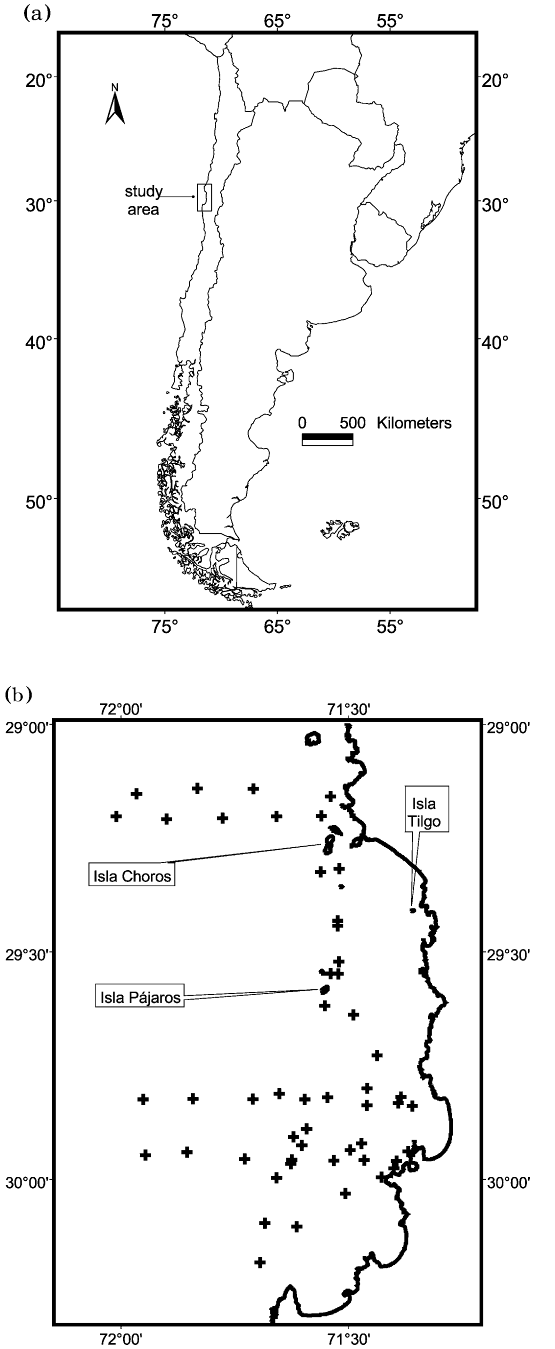

Figure 1. (a) Location of the study area in northern Chile and (b) close-up (black crosses: hydrographic stations; labelled sites: important breeding colonies).

station approximately midway and 10 min intervals in two opposite directions (with a minimum of 4 km and a maximum of 8 km in either direction from the station). Only the commoner species with numbers sighted exceeding 1% of all individuals counted (Table 1) were included in the analysis. Density by species and seven environmental variables were included in the analysis: (1) water depth (Anon., 1999), (2) distance to nearest land, (3) number of trawlers within a radius of 5 km, (4) sea surface temperature, sea surface temperature minus water temperature in (5) 10 m and (6) 30 m, and (7) the difference between temperature at 10 and 50 m depth. Salinity was excluded, because it was virtually constant throughout the study area. Although the number and distribution of chlorophyll measurements obtained were insufficient for inclusion in statistical analyses, the data did provide a general distribution pattern from which inferences could be made in relation to the distribution of seabirds. Only principal components with eigenvalues >1 were included in the model, and axes were varimax-rotated to facilitate interpretation (Backhaus *et al.*, 1996).

Seabird assemblages were analysed using cluster analysis. Species densities were selected as variables and counting intervals (7−19 min), derived from the original 10 min intervals (see above), were selected as cases. Only species seen in at least five counting intervals were included, an arbitrary choice that allowed covering a wide spectrum of species while ignoring species with few occurrences. Data were standardized by z-transformation. Following recommendations of Backhaus *et al.* (1996), we used the Ward method with Euclidean distance as similarity coefficient.

Results

A total of 24 species was recorded with the Peruvian booby, Humboldt penguin and kelp gull being the most abundant (Table 1). The distribution patterns differed substantially among eight of the more abundant species (Figure 2). Most species showed apparent links to variation in environmental factors, particularly to trawler distribution (Figure 2g, h), centres of upwelling of cold water (Figure 2d−f) and chlorophyll concentrations (Figure 2b, c).

The proportion of divers (Peruvian booby, Humboldt penguin, and Peruvian diving-petrel) decreased significantly as a function of distance to the coast (Spearman rank correlation $r_s = -0.279$, $p < 0.01$, $n = 87$ grid cells). Also, the proportion of surface-feeding birds (white-chinned petrel, Juan-Fernandez petrel, Antarctic prion, kelp gull, and Franklin's gull) and of diving birds (see above) differed significantly among three classes of distances to the coast (0−10 km, 10−30 km, 30−53.4 km; $\chi = 206$; $df = 2$, $p < 0.001$), with the former being relatively more numerous further offshore and the latter more numerous closer to the coast.

Analysis of environmental variables and seabird density by PCA revealed that six components explained 78% of the variance in all variables (Table 2). A feeding-flock factor including Peruvian booby, Humboldt penguin, guanay cormorant and grey gull was identified as the most important factor, followed by a hydrographic factor and a factor reflecting the distance to the coast and depth (Table 3).

Cluster analysis revealed two main clusters (Figure 3). One consisted of Humboldt penguins, guanay cormorants, Peruvian boobies, and grey gulls (forming the typical feeding-flock species) and the other one of species that were to a much lesser extent or not at all engaged in feeding flocks and did not show this behaviour (Table 4).

Seven species were found to directly attend fishing trawlers. The highest percentage of individuals following trawlers was observed for Chilean pelican (53%), followed by Buller's albatross (17%), Franklin's gull (9%), Kelp gull (8%), white-chinned petrel (5%), Peruvian booby (1%) and Antarctic prion (1%). Overall, 3% of all seabirds observed were attending fishing vessels.

Discussion

Many of the species observed showed distinct distribution patterns and the PCA indicates that these are related to various environmental factors. However, the interpretation of these relationships is not straightforward, because ultimately distribution of different seabirds is expected to reflect the availability of their preferred prey and the question is how these prey are affected by the environment.

The distribution of sea surface temperatures indicates a major upwelling area in the southern part of the Coquimbo area, where Juan-Fernandez petrels (Figure 2e), Antarctic prions (Figure 2f) and white-chinned petrels (Figure 2d) were also concentrated. These species showed similar distribution patterns and were grouped closely in both cluster analysis and PCA. We can only speculate about the reasons for the association between their distribution and cold surface waters. Their common feeding technique offers one possible explanation. All three species search for food at or close to the sea surface. White-chinned petrels feed on a variety of prey items including crustaceans (mainly Euphausids), pelagic fish, squid, salps (Jackson, 1988; Croxall *et al.*, 1995; Catard *et al.*, 2000) and have been observed behind fishing vessels (Warham, 1996; Yorio and Caille, 1999). Literature on the feeding behaviour of the other two species is scarce, but Antarctic prions feed also on Euphausids and small fish (Prince, 1980; del Hoyo *et al.*, 1992) and Juan-Fernandez petrels probably feed on squid and fish (del Hoyo *et al.*, 1992).

Upwelling is supposed to enhance nutrient availability and consequently phytoplankton production. Unfortunately, chlorophyll could not be measured at all stations and therefore this index of primary production had to be excluded from the PCA. Nevertheless, the available information suggests some association between the distribution of Humboldt penguin (Figure 2b), kelp gull (Figure 2g), and Franklin's gull (Figure 2h) and the integrated chlorophyll values over the upper 50 m of the water column. Phytoplankton is the main prey of pelagic schooling fishes such as anchovies and sardines (Rojas de Mendiola 1980; Arntz and Fahrbach, 1991; Arrizaga *et al.*,

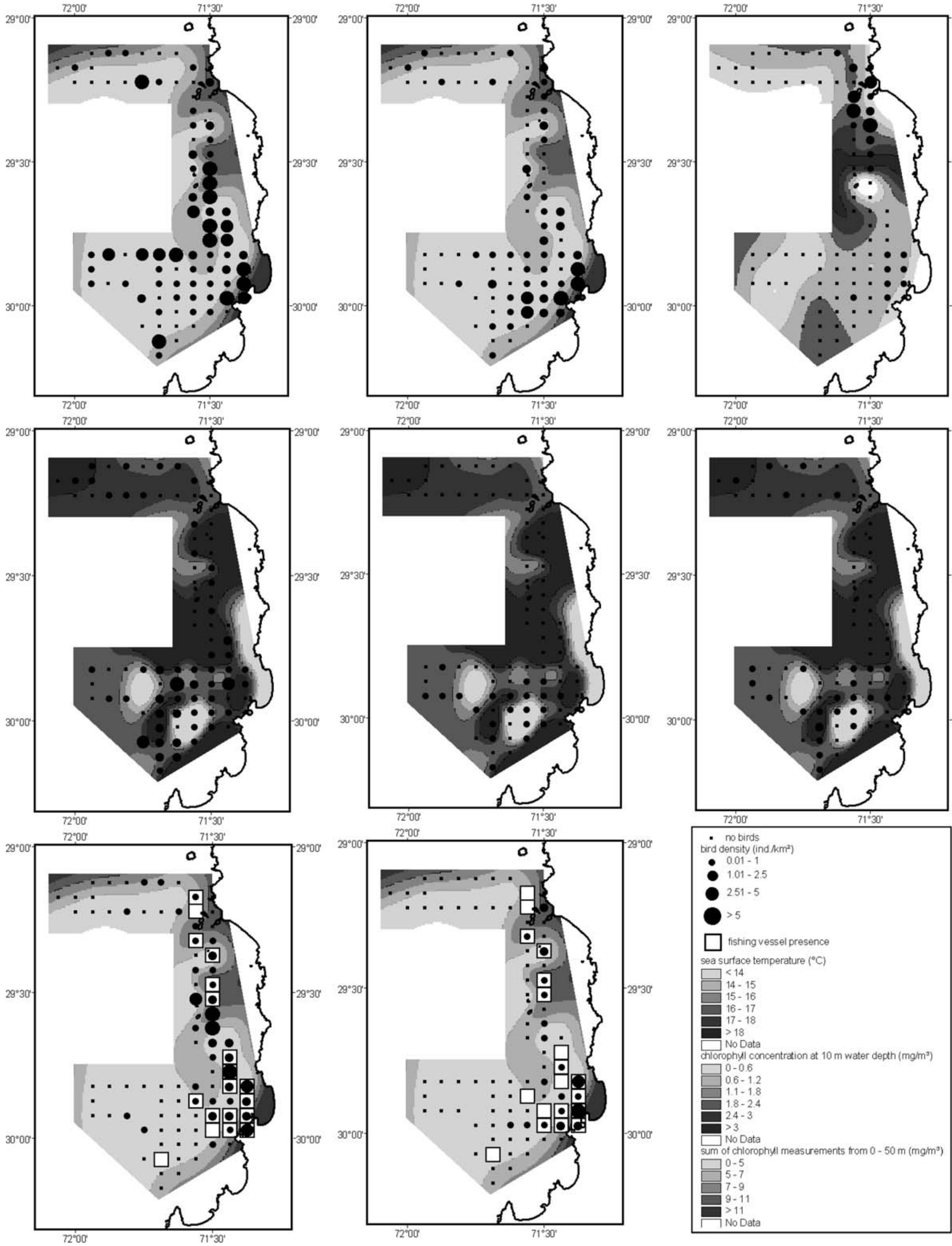

Figure 2. Distribution of (a) Peruvian booby and chlorophyll (integrated values 0–50 m), (b) Humboldt penguin and chlorophyll (integrated values 0–50 m), (c) Peruvian diving-petrel and chlorophyll (at 10 m depth), (d) white-chinned petrel and SST, (e) Juan-Fernandez petrel and SST, (f) Antarctic prion and SST, (g) kelp gull and chlorophyll (integrated values 0–50 m), and (h) Franklin's gull and chlorophyll (integrated values 0–50 m), January 1999 (fishing vessel presence is shown in g and h).

Table 2. Eigenvalues and percentages of variation explained by the six principal components and the corresponding loadings for the 11 species and seven environmental variables derived from the correlation matrix and subsequent rotation (values in bold were used to characterize each component).

	PC1	PC2	PC3	PC4	PC5	PC6
Eigenvalue	3.62	2.78	2.72	1.91	1.64	1.42
Variation explained (%)	20.1	15.4	15.1	10.7	9.1	7.9
SST	−0.07	**0.93**	−0.08	−0.10	0.03	0.05
ΔT (surface−10 m)	−0.19	0.59	0.46	−0.18	0.23	0.05
ΔT (surface−50 m)	0.01	**0.94**	0.17	−0.08	0.11	0.11
ΔT (10 m−30 m)	0.33	**0.62**	0.30	−0.17	−0.13	0.06
Distance to nearest land	−0.19	−0.16	**−0.86**	0.03	−0.10	−0.23
Depth	−0.15	−0.13	**−0.84**	−0.05	−0.09	−0.24
Number of trawlers	−0.04	0.28	0.44	0.06	−0.02	0.59
Franklin's gull	0.43	0.04	0.10	−0.07	**0.80**	−0.05
Grey gull	**0.68**	0.01	0.04	−0.06	**0.65**	−0.06
Kelp gull	−0.03	0.24	0.51	−0.11	0.47	−0.20
Juan-Fernandez petrel	−0.03	0.04	−0.11	**0.71**	−0.10	−0.10
White-chinned petrel	−0.17	−0.17	0.29	**0.77**	0.00	−0.08
Antarctic prion	−0.05	−0.26	−0.13	**0.81**	0.01	0.04
Buller's albatross	0.00	−0.08	0.59	−0.04	−0.43	−0.39
Peruvian diving-petrel	−0.02	0.02	0.08	−0.17	−0.08	**0.85**
Humboldt penguin	**0.96**	0.00	0.07	−0.07	0.08	0.00
Peruvian booby	**0.94**	0.02	0.08	−0.08	0.04	−0.01
Guanay cormorant	**0.96**	−0.01	0.05	−0.07	0.22	−0.01

1993), which are favourite prey of the Humboldt penguin (Wilson and Wilson, 1988), the Peruvian booby (Tovar *et al.*, 1988; Jahncke and Goya, 1998; Jahncke and Zileri, 1998) and the Neotropical cormorant (Tovar and Guillén, 1989).

The Peruvian diving-petrel (Figure 2c) had two distribution centres in the Coquimbo area, one with low densities in the upwelling area to the south and one with high densities situated directly south of Isla Choros. The upwelling area appears to be too far away to be exploited effectively by breeding birds from the colony on Isla Choros (Figure 4) and we presume that the birds seen there were non-breeding individuals.

Interestingly, a chlorophyll maximum existed at 10 m depth just south of Isla Choros, presumably caused by upwelled water from the northern focus advected southward (Acuña *et al.*, 1989). The Peruvian diving-petrels were observed in the direction of this maximum. Because this species dives deep for food (average maximum dive depth 31 m; Zavalaga and Jahncke, 1997), a food source at a depth of 10 m can be easily utilized. None of the other species showed such high densities near the isle. Thus, the food supply around Isla Choros appears to be fundamentally different from the central and southern parts of the Coquimbo area. The Peruvian diving-petrel feeds mainly on planktonic invertebrates with *Euphausia mucronata* as the main prey (Jahncke *et al.*, 1999). In contrast, fish-eating seabirds were only observed in low densities in the area around Isla Choros, even though quite a few breed there.

Table 3. Characterization of the six principal components.

PC1	Feeding-flock component with Peruvian booby, Humboldt penguin, guanay cormorant, and grey gull as typical species
PC2	Hydrographic factor with SST, ΔT (surface−50 m), and ΔT (10 m−30 m)
PC3	Land−sea gradient with distance to nearest land and depth
PC4	Interaction among offshore species (Juan-Fernandez petrel, Antarctic prion, and white-chinned petrel)
PC5	Interaction between Franklin's gull and grey gull
PC6	Peruvian diving-petrel

Studies in other parts of the world, such as the North Sea, have shown that fishing activities may have a considerable influence on seabirds. Particularly discards are an additional, easily accessible food resource for many species (Camphuysen *et al.*, 1995; Garthe *et al.*, 1996) and spatial and temporal differences in availability of discards affect their distribution (Garthe, 1997). During this study, we observed seven seabird species attending fishing vessels. In addition, during two trips on the commercial trawler "Don Antonio" (1−2 and 4 February 1999, respectively), we observed large numbers of kelp gulls (maximum 600), Franklin's gulls (840), grey gulls (310), Peruvian boobies (400) and Inca terns (310) feeding behind the vessel. Other authors have also observed kelp gulls behind fishing vessels (Abrams, 1983; Ryan and Moloney, 1988; Bertelotti and Yorio, 2000) and Franklin's gulls are known to feed partly on discards (del Hoyo *et al.*, 1996). These two species, Franklin's gull (Figure 2h) and kelp gull (Figure 2g), showed nearly the same distribution pattern in the transect study as the presence of fishing vessels. Yet, fishing activities do not seem to have a strong influence on the

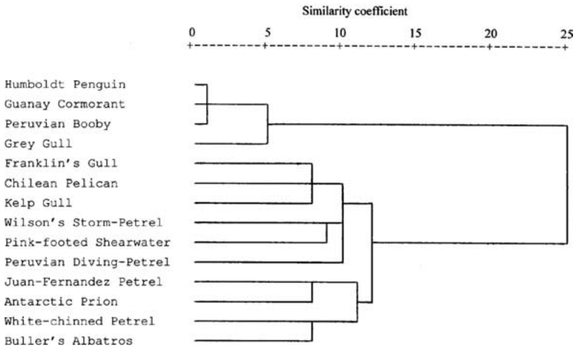

Figure 3. Similarity dendrogram for seabirds at sea (abundances at counting intervals) according to cluster analysis.

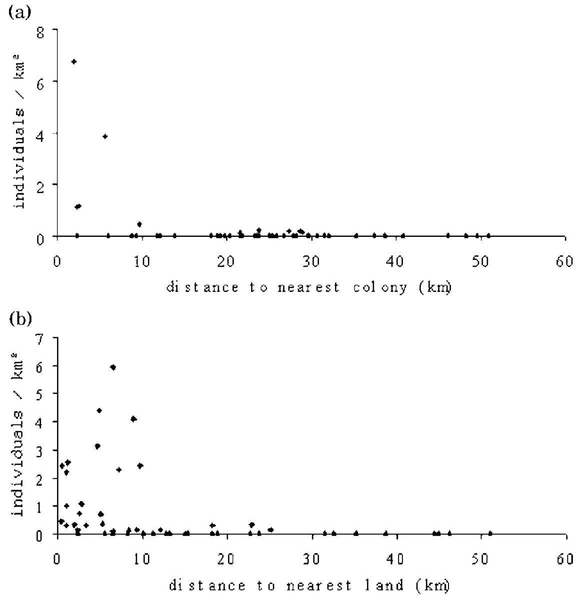

Figure 4. Densities of (a) Peruvian diving-petrels and (b) kelp gulls in relation to the distance to the nearest breeding colony (differences were tested with the Kruskal–Wallis H-test: a: $\chi^2 = 13.7$; df = 4; $p < 0.05$; b: $\chi^2 = 25.8$; df = 4; $p < 0.05$).

distribution of seabirds and proportions of ship-followers were remarkably low compared to many other oceans.

In conclusion, the distribution of seabirds in the Humboldt Current system of northern Chile can be related to major abiotic and biotic factors. A prominent feature was the presence of feeding flocks comprising different species and accounting for one-third of all birds recorded during transect counts. Surface feeders and shallow divers such as the Juan-Fernandez petrel and Antarctic prion occurred relatively far offshore whereas deep divers such as the Humboldt penguin and Peruvian diving-petrel were most frequently observed in inshore waters, suggesting changes in predominant feeding mode as a function of distance to the coast.

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Table 4. Number of individuals per species recorded, listed separately for those joining feeding flocks (FF) and those outside (only species with >50 individuals listed).

Species	Total	FF	Outside	% FF
Grey gull	119	113	6	95
Guanay cormorant	54	44	10	82
Humboldt penguin	617	334	283	54
Peruvian booby	1287	594	693	46
Buller's albatross	142	11	131	8
Franklin's gull	204	14	190	7
Kelp gull	424	6	418	1
White-chinned petrel	287	2	285	1
Juan-Fernandez petrel	56	0	56	0
Antarctic prion	79	0	79	0
Peruvian diving-petrel	130	0	130	0
Others	89	0	89	0
Total	3488	1118	2370	32

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