

Oceanographic and biological landscapes used by the Southern Giant Petrel during the breeding season at the Patagonian Shelf

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Abstract The study of how and why marine animals distribute themselves at sea has important conservation and management implications of the species and their habitats. We characterize the oceanographic and biological landscapes of the marine areas used by breeding Southern Giant Petrels (*Macronectes giganteus*) at Patagonian colonies and explore inter-sexual and inter-colony differences. The at-sea movements of 16 adults (7 males and 9 females) were studied by means of satellite telemetry techniques during 1999, 2000, 2002, and 2004 breeding seasons. Southern Giant Petrels utilized an oceanographic scenario characterized by high productivity, warm sea surface temperature, and shallow waters. The biological landscape was characterized by a high availability of squid and carrion nearby colonies. Females spent more time in the shelf break

and exploited deeper waters than males. In contrast, males spent more time in coastal areas and they showed a higher spatial overlap with areas of high squid density than females. Such a prosperous foraging scenario for both sexes may play a key role in the growth of the breeding population of Southern Giant Petrel Patagonian colonies.

Introduction

The study of how and why animals distribute themselves in space has important conservation and management implications of the species and their habitats. When little is known about the ecology of a species, models can be used to explore empirical associations between animal distributions and the physical and biological features of the area (see Redfern et al. 2006 for a marine example). Overlaying seabird distributions on maps of physical oceanographic variables, such as bathymetry (Yen et al. 2004), sea surface temperature, or chlorophyll concentration (Hyrenbach et al. 2002; Awkerman et al. 2005; Phillips et al. 2006), provide valuable information on factors potentially contributing to the spatio-temporal variability of wide-ranging species. Consequently, understanding the spatial pattern and distribution boundaries of the species is also useful for predicting potential conflicts with human activities (Nel et al. 2002; Cuthbert et al. 2005; Terauds et al. 2006).

The Southern Giant Petrel (SGP, *Macronectes giganteus*) is a wide-ranging procellariiform with a circumpolar breeding distribution (Carboneras 1992) and is considered one of the dominant scavengers of the Southern Atlantic Ocean (Hunter 1983; Hunter and Brooke 1992). The species was considered ‘Near Threatened’ under IUCN criterion until 2008 and was recently uploaded to ‘Least

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Table 1 Summary of satellite telemetry data obtained from instrumented Southern Giant Petrels from Patagonian colonies during the breeding period (Adapted from Quintana et al. 2010)

Individual	Sex	Colony	Start tracking	End tracking	Total days recorded	Hours of tracking
Northern colonies						
5,609	M	Gran Robredo	09/01/1999	31/01/1999	22	528
5,819	F	Gran Robredo	09/01/1999	22/02/1999	43	1,054
25,135	F	Gran Robredo	26/11/1999	23/01/2000	57	1,393
25,138	M	Gran Robredo	27/11/1999	20/01/2000	53	1,299
10,100	M	Arce	03/01/2002	22/02/2002	49	1,197
10,101	F	Arce	04/01/2002	24/02/2002	50	1,247
10,102	M	Arce	03/01/2002	28/02/2002	55	1,258
10,103	M	Arce	04/01/2002	06/01/2002	2	58
10,104	M	Arce	06/01/2002	16/01/2002	10	250
Southern colony						
44,281	M	Observatorio	06/01/2004	10/03/2004	64	1,386
44,282	F	Observatorio	06/01/2004	11/01/2004	5	124
39,792	F	Observatorio	06/01/2004	12/01/2004	6	137
39,791	F	Observatorio	06/01/2004	09/01/2004	3	69
39,793	F	Observatorio	09/01/2004	08/03/2004	59	1,399
39,794	F	Observatorio	12/01/2004	02/03/2004	50	1,197
44,283	F	Observatorio	12/01/2004	04/02/2004	22	546

Concern (BirdLife International 2009), reflecting a greater understanding of the species and its global population. It is also listed on Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (www.cms.int) and is included on Annex 1 of the recent Agreement on the Conservation of Albatrosses and Petrels (ACAP, www.acap.aq). In Patagonia, Argentina, the SGP breeds at four colonies (with the exception of Malvinas/Falklands colonies), two of which are localized in Chubut Province (Isla Arce 45°00'S, 65°29'W; Isla Gran Robredo 45°8'S, 65°4'W) and the other two in Tierra del Fuego (Staten Island) (Isla Observatorio 54°39'S, 64°8'W, and Península López 54°54'S, 64°39'W) (Quintana et al. 2005; 2006). Located in the large marine ecosystem of the Patagonian Shelf, the Argentinean colonies are surrounded by temperate waters and neritic systems. In contrast, most of the remaining SGP colonies worldwide are situated in the cold Antarctic and Subantarctic waters (Patterson et al. 2008).

In a previous study, Quintana et al. (2010) found differences in the SGP foraging behavior and habitat use between sexes and colonies. Consequently, we expected that in the oceanographic and biological landscapes SGPs would show also sexual and colonial segregation. The objective of this study was to characterize the oceanographic and biological features of the marine areas foraged in by breeding SGPs at Patagonian colonies and explore inter-sexual and inter-colony differences.

Methods

The at-sea movements of breeding SGP during the chick-rearing period were studied by means of satellite telemetry techniques (see Quintana et al. 2010 for more details about foraging behavior). A total of 9 adults (6 males and 3 females) from Isla Arce and Isla Gran Robredo (northern colonies) and 7 adults (1 male and 6 females) from Isla Observatorio (southern colony) were fitted with satellite transmitters (PTTs-100, “Platform Terminal Transmitters”, Microwave Telemetry) during four breeding seasons 1999, 2000, 2002, and 2004 (Table 1). Birds were capture from the nest using a 2-m stick with a metal hook. Satellite transmitters weighted between 45 and 90 grs representing less than 3.6% of the animal’s body weight. Instrumented birds were sexed by morphometric measurements and by blood samples (see Copello et al. 2006). Individual positions were recorded by the ARGOS system filtered and then re-sampled every hour following the iterative procedure used by the “Global Procellariiform Tracking Database” (BirdLife International 2004). A Kernel analysis (“fixed kernel method”, Worton 1989) was employed to analyze the habitat use and the amount of time spent at different marine areas. We used the “Animal Movement Program” package of ArcView 3.0 to determine the areas where animals spent 95, 75, and 50% of their foraging time.

The oceanographic habitat of the SGP in the Patagonian Shelf was defined using: oceanographic regimes; sea sur-

face temperature (hereafter SST); chlorophyll-a concentration; and the bathymetry of the area. Oceanographic regimes were characterized using the salinity isohalines following Piola (2003) and tidal fronts according to Rivas et al. (2006). Nine oceanographic regimes were considered: (1) Patos, (2) Plata, (3) Subtropical, (4) Mix, (5) Subpolar, (6) Shelf Break, (7) Open Shelf, (8) Magellan, and (9) Tidal fronts. SST and chlorophyll satellite images were obtained from PO DAAC Physical Oceanography DACC <http://poet.jpl.nasa.gov> using AVHRR Pathfinder Version 5 satellite and the Distributed Active Archive Center DAAC in the Goddard Space Flight Center by means of the SeaWiFS satellite. For both variables, SST and chlorophyll, average monthly images with a spatial resolution of 4 km were used. These images corresponded to January 1999, 2000, and 2002 (northern colonies) and January 2004 (southern colony). In all cases, satellite images temporally match with the period when the birds were tracked. The bathymetry was obtained from the GEBCO database with a spatial resolution of 2 km. We calculated the percentage of time that birds spent in the oceanographic regimes and areas with particular SST, chlorophyll concentration, and depth, by using the “Grid Analyst” and “Spatial Analysis” extension in the ArcView 3.2 ESRI. We divided the Patagonian Shelf and surrounding areas in five bathymetric domains: <100 m, between 100 and 200, between 200 and 1,000 and >1,000 m. Four productivity regimes were considered based on remotely sensed chlorophyll standing stocks: oligotrophic (<0.1 mg m⁻³), mesotrophic (0.1–0.3), eutrophic (0.3–1), and enriched (>1 mg m⁻³) (Hyrenbach et al. 2002; Louzao et al. 2006). Six temperature ranges were defined for describing the SST areas: 1–4, 4–8, 8–12, 12–15, 15–19, and 19–23°C. A Mann–Whitney test was used to determine differences in each oceanographic habitat between sexes and colonies.

The biological landscape was defined considering the distribution and abundance of the main prey items reported by the SGP from the northern colonies. Known prey species included: the squid (*Illex argentinus*), the Magellanic Penguin (*Spheniscus magellanicus*), and the Southern Sea Lion (*Otaria flavescens*) (Copello et al. 2008). The distribution and abundance of squid stocks, penguin colonies, and of sea lion rookeries along the Patagonian coast were considered as indicators of prey and carrion availability. Distribution maps of squid stocks were created using records from stocks assessment studies by the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) (Brunetti et al. 1998). Similar to the SGP habitat use analysis, a non-parametric density function (kernel analysis) was used to determine areas with different levels of abundance of penguin and sea lion carrion. Then, we overlay the generated maps (SGP kernel maps and kernel maps of the main prey items) to analyze their overlap. To determine the utilization

of coastal areas, we calculated the time that birds spent in an area distant by 3 km from the coastal line to the sea and by 3 km from the coastal line to the land.

Results

Oceanographic landscape

Oceanographic regimes

During the late incubation and chick-rearing period (November–March), SGPs used marine areas included in five of the nine oceanographic regimes of the Southwest Atlantic Ocean (see “methods”): the Open shelf, the Magellan area, the Shelf break, the Subpolar regime, and Tidal fronts (Figs. 1 and 2). The Open shelf regime was used during more than 40% of the time at sea. In less than 10% of the time at sea, breeding SGPs used the regimes of the Shelf break and Magellan (except for the male from the southern colony which remained mainly in the Magellan regime) and during less than 5% of the time at sea the birds used several Tidal fronts and the Subpolar regime (Figs. 1, 2).

Data from the northern colonies showed that females remained more time in the Shelf break than males (10.0 vs. 0.7%, $U = 1$, $P < 0.05$), whereas the other regimes were used in a similar way for both sexes (83.2 vs. 86.4%, 11.3 vs. 0.7%, 0 vs. 0.2%, 4.8 vs. 2.6%, for the Open shelf, the Magellan area, the Subpolar regime, and the Tidal fronts, respectively, $U > 2$, $P > 0.05$). The females from the southern colony also remained for longer at the Shelf break than the only tracked male (10.4 vs. 0.5%), who stayed most of the time at sea in the Magellan regime (56.2 vs. 3.1%). The Tidal fronts were mainly used for the northern colonies birds (4.1 vs. 0.03%, $U = 0$, $P < 0.01$) (Figs. 1, 2).

Bathymetry

The at-sea tracking data from SGPs revealed foraging throughout a vast range of depths, from shallow waters (<100 m, 62.5–89.7%) to the deep waters (>1,000 m, 0.01–1.7%). However, 60% of the time birds utilized waters less than 100 m deep (Figs. 1, 3).

There was no difference between female and male SGP in the range of water depths lesser than 200 m (northern colonies: $U_{<100} = 3$ and $U_{100-200} = 5$, $P > 0.1$; Fig. 3). A similar pattern was observed for southern females and the only male instrumented at Isla Observatorio (Fig. 3). However, in both nesting sites, waters deeper than 200 m (200–1,000 m) were used mainly by females (5.2 vs. 0.2% of time at sea, for females and males from the northern colonies, $U = 1$, $P < 0.05$, and 21.8 versus 0.4% for females and male from the southern colony, Fig. 1). There were no inter-colony

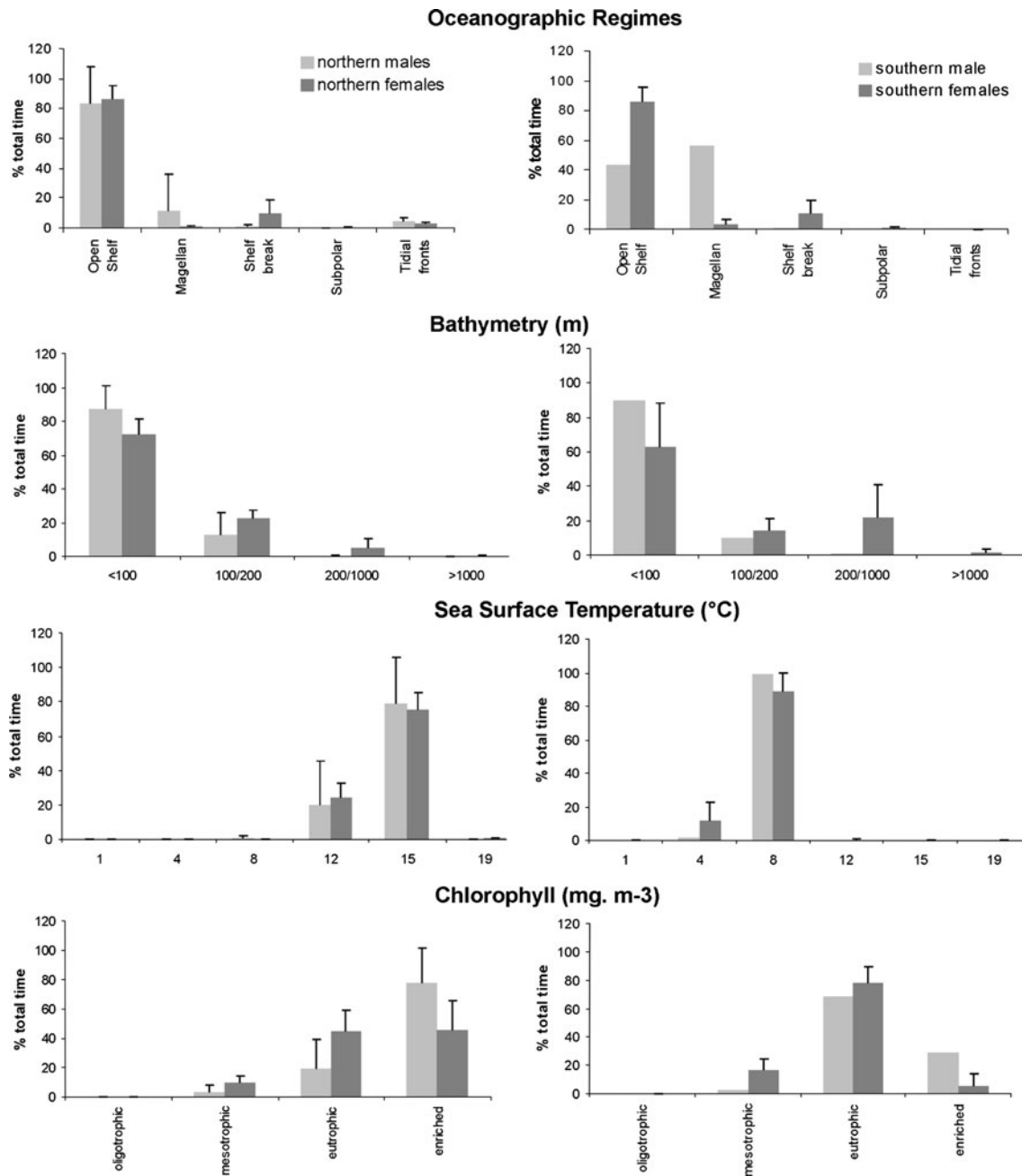


Fig. 1 Proportion of time satellite tracked Southern Giant Petrels spent in different oceanographic landscapes (oceanographic regimes, bathymetry, sea surface temperature, and chlorophyll concentration) during the breeding period

differences in the depth of the marine areas used (<100 m 62.5 vs. 72.1%, 100/200 m 14.0 vs. 22.5%, 200/1,000 m 21.8 vs. 5.2%, and >1,000 m 1.7 vs. 0.2% for southern females and northern females, respectively; $U > 3$, $P > 0.1$).

Sea surface temperature

SGPs from both nesting sites used marine areas with surface temperatures between 4 and 23°C, but they remained most of the time at sea in waters between 8 and 19°C (Figs. 1, 4). Males and females spent similar times in each

temperature range ($U > 6$, $P > 0.1$ for northern colonies) (Fig. 1). The SST of the marine areas exploited by SGPs from northern colonies was warmer than those used from birds from Isla Observatorio and there was no overlap in the temperature ranges (Fig. 1).

Chlorophyll concentration

During the study period, SGPs ranged over areas of different productivity levels, from mesotrophic to enriched waters, with no excursions into low productivity waters (oligo-

Fig. 2 At-sea distribution of the Southern Giant Petrel from northern and southern colonies (see text) in relation to oceanographic regimes (*stars in the left panel*: location of the study colonies)

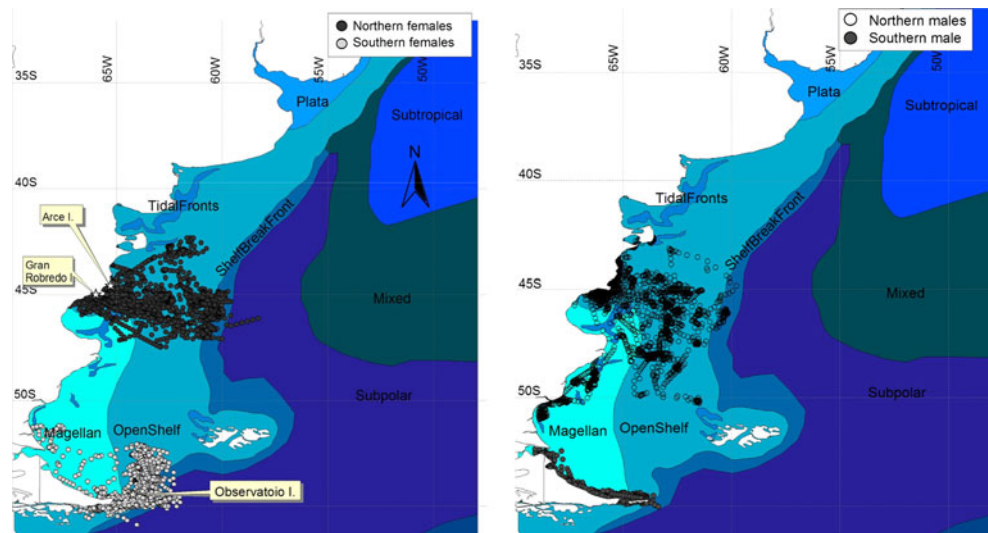
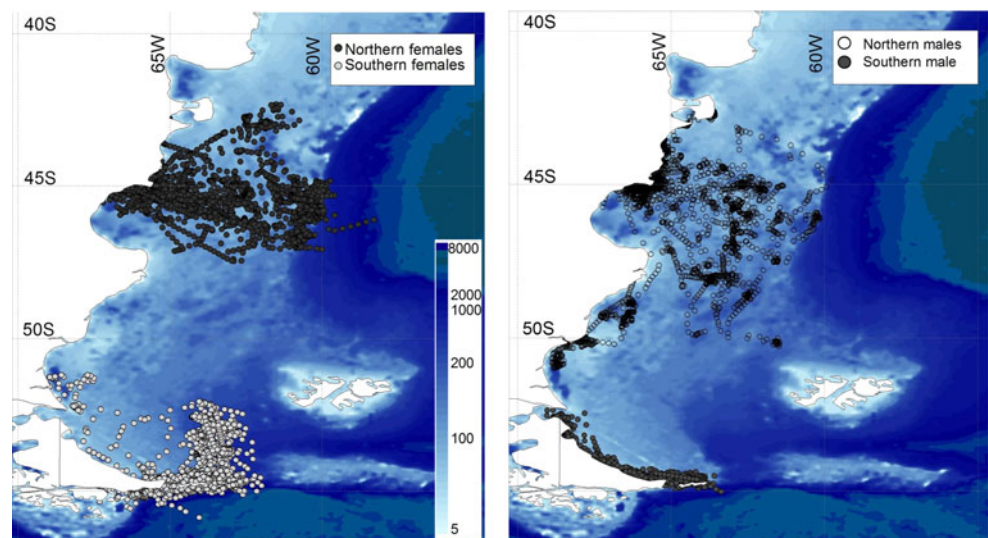


Fig. 3 At-sea distribution of the Southern Giant Petrel in relation to bathymetry (m)



trophic) (Figs. 1, 5). The birds spent most of their time at sea (~90%) in eutrophic and enriched waters. At the northern colonies, both sexes spent similar percentage of time in mesotrophic, eutrophic, and enriched waters ($U > 2$, $P > 0.05$). In the southern colony, the only studied male extended over enriched waters longer time than females (29 vs. 6%). SGP from the northern colonies spent more than 50% of their time at sea in areas of high productivity (enriched) ($U = 0$, $P < 0.01$), while southern birds spent most of their time (80%) in waters of lower productivity (eutrophic and mesotrophic) ($U = 10$, $P < 0.05$) (Fig. 1).

Biological landscape

Squid

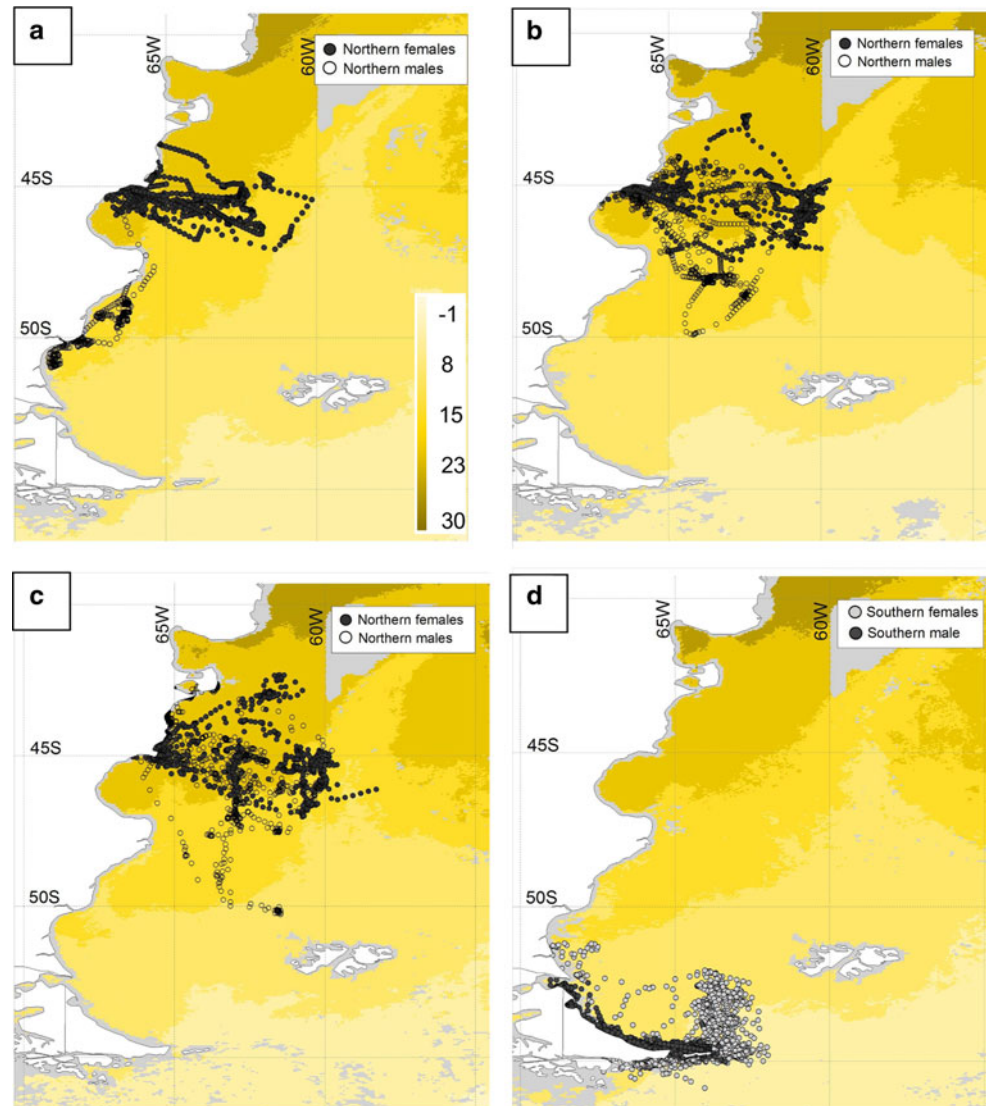
The at-sea distribution of males and females SGP from the northern colonies showed a high spatio-temporal overlap

with the distribution range of the squid at the Patagonian Shelf. There was also a clear spatial convergence with areas of high squid abundance located between 43 and 51°S (Fig. 6). Those assemblages corresponded to the ‘summer spawning stock’ (SDV) and the ‘south-patagonic stock’ (SSP) (Fig. 6, Brunetti et al. 1998). While males from the northern colonies mainly exploited areas of high squid abundance, females from the same nesting site used both low and high abundance areas (Fig. 6). On the contrary, SGP from Isla Observatorio showed almost no spatio-temporal overlap with the squid distribution; females partially ranged over areas of low squid abundances, while the male SGP did not overlap with the squid distribution (Fig. 6).

Sea lion and penguin carrion

We identified 104 Southern Sea Lion rookeries (Reyes et al. 1999; Schiavini et al. 1999; Dans et al. 2004) and 66

Fig. 4 At-sea distribution of the Southern Giant Petrel in the years 1999 (a), 2000 (b), 2002 (c), and 2004 (d) in relation to the sea surface temperature (°C) in the same seasons. *Light gray* areas: no temperature data



colonies of the Magellanic Penguin and the Rockhopper Penguin (*Eudyptes chrysocome*) (Schiavini et al. 2005) along the Patagonian coast of Argentina. The greatest density of sea lions was located at the North of San Jorge Gulf between 44.7° and 45.5°S, and Valdes Peninsula between 42° and 43°S (Fig. 7). Furthermore, the greatest densities of penguins were located also at the North of San Jorge Gulf, between 44.9° and 45.2°S, at the surroundings of Punta Tombo area between 44.9° and 45.2°S, and at the West of Staten Island between 54.5° and 55.1°S (Fig. 7).

Females and males from the northern SGP colonies showed a clear spatio-temporal association with areas of high densities of penguin and sea lions. They spent half of their time in areas with high density of potential carrion that was located in the North of San Jorge Gulf in the vicinity of the two northern nesting sites (Isla Arce and Gran Robredo) (Fig. 7). Punta Tombo and its adjacent areas were used

mainly by males (kernel 50%), but not by females (Fig. 7). Birds from Isla Observatorio also showed a spatio-temporal overlap with areas containing high density of penguin but low sea lion concentrations (Fig. 7). In this case, southern female SGPs spent 50% of the total time in areas of high density of penguins in the vicinity of the colony (Fig. 7), while the only male tracked at Isla Observatorio, explored more distant coastal areas with (Magallanes Strait) almost no penguins availability and low sea lion density (Fig. 7). There was a clear overlap between the distributions of male SGPs with areas of high carrion availability than from females in both nesting sites (mainly for the northern colonies). Males from the northern colonies spent more time than females in coastal areas (25.3 ± 28.1 vs. $2.4 \pm 0.3\%$, $U = 0$, $P < 0.05$). A similar pattern was observed for birds from the southern colony (30.9% vs. $7.3 \pm 2.7\%$ for the male and females, respectively).

Fig. 5 At-sea distribution of the Southern Giant Petrel during 1999 (a), 2000 (b), 2002 (c), and 2004 (d) in relation to the chlorophyll concentration (mg m^{-3}) in the same seasons. *Black areas*: no chlorophyll data

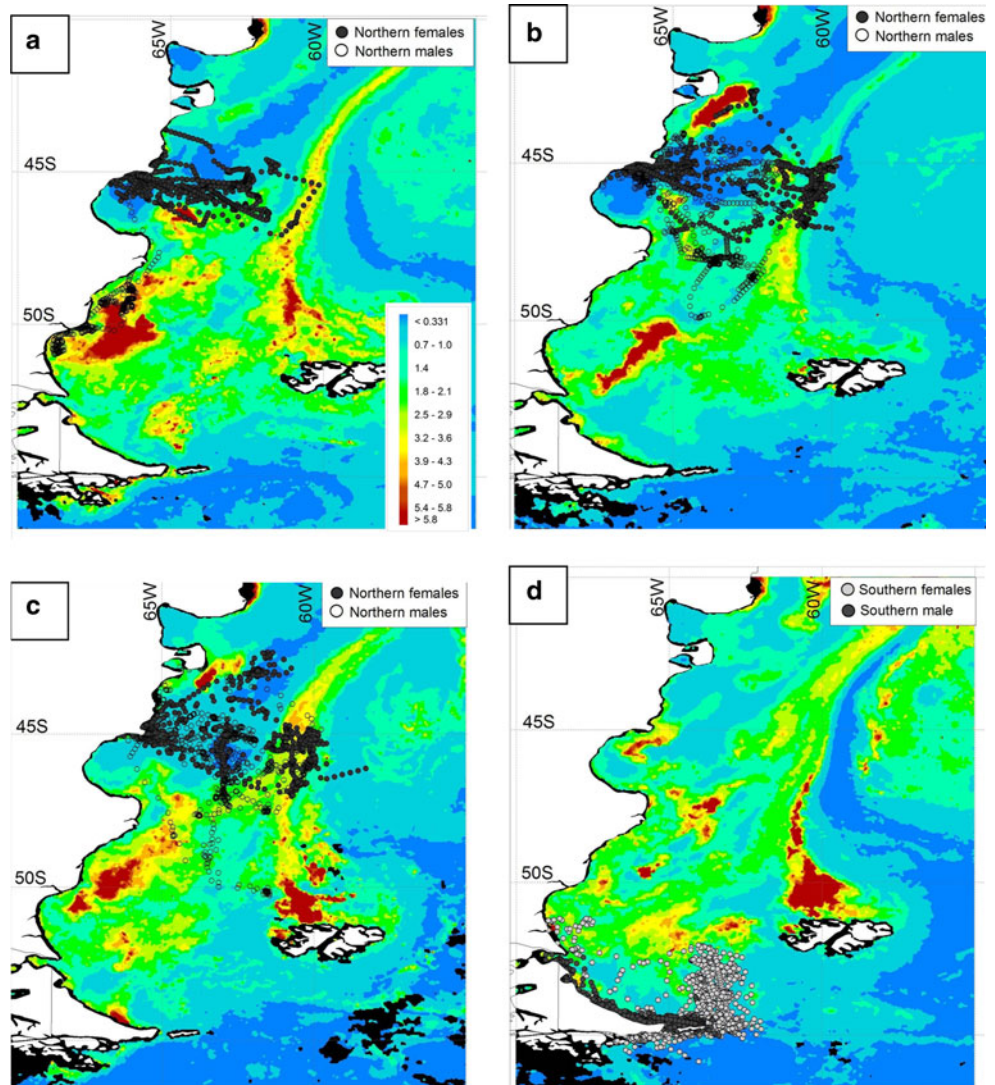


Fig. 6 Squid distribution (*Illex argentinus*) during the summer period. (Adapted from Brunetti et al. 1998) and habitat use (kernel, see text) of females (left) and males (right) from the northern and southern colonies

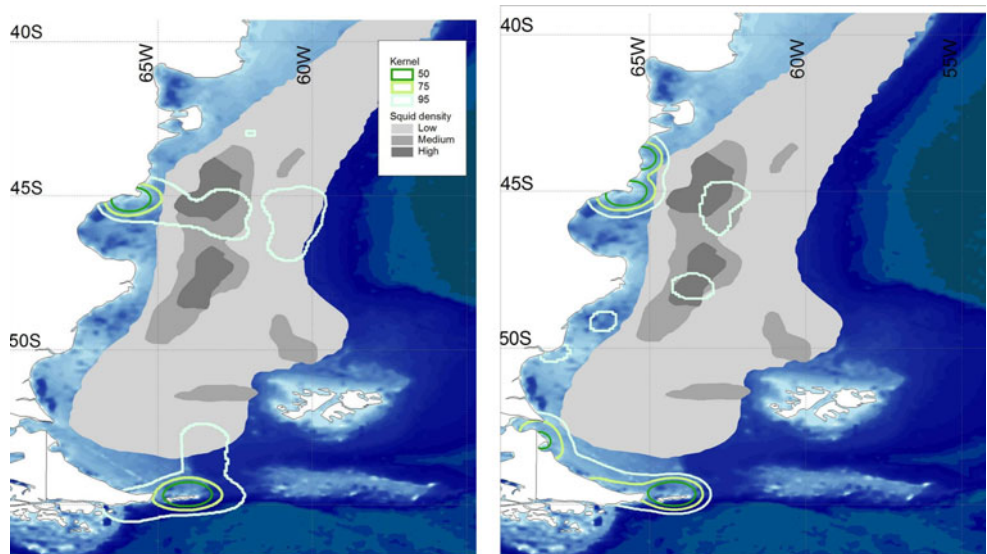
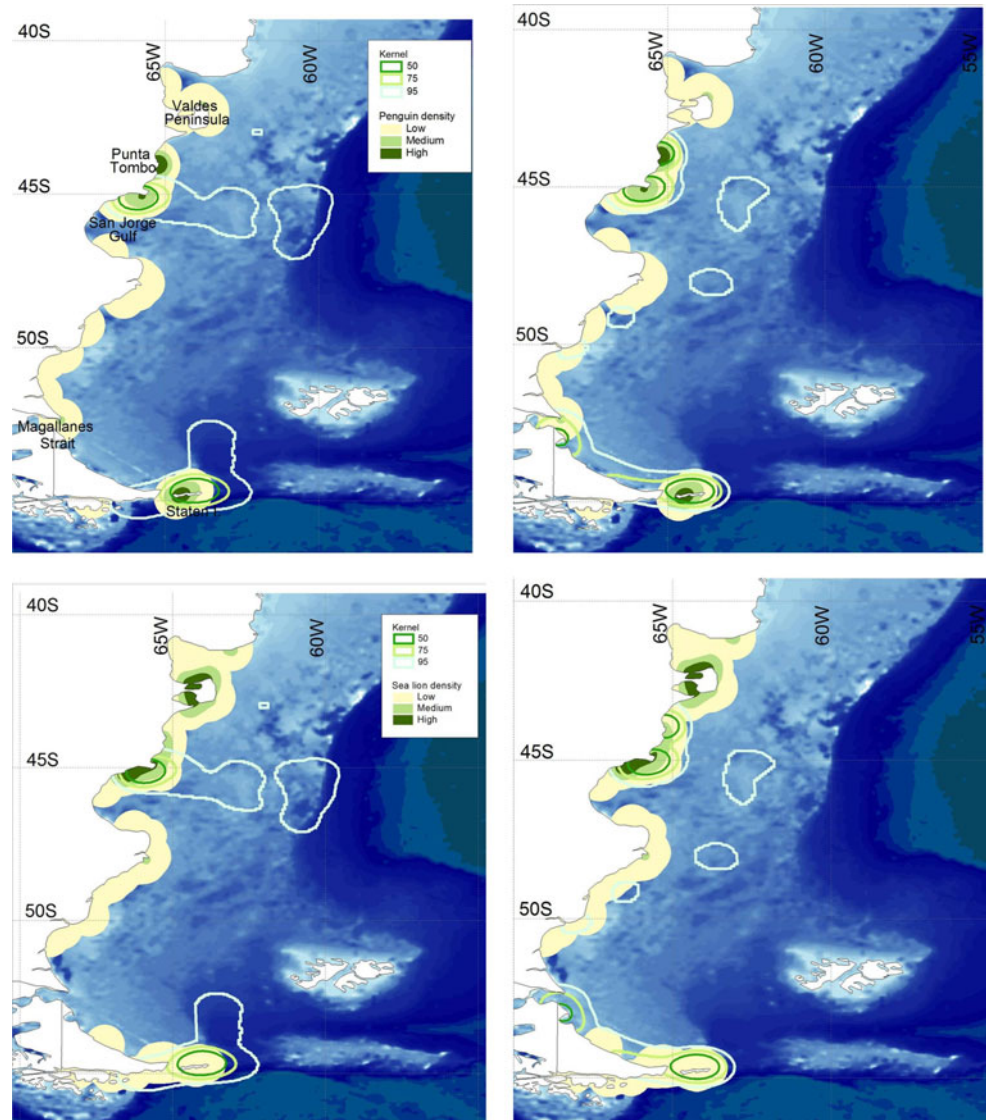


Fig. 7 Carrion distribution in the Patagonian coast and habitat use (kernel, see text) for females (*left*) and males (*right*) of Southern Giant Petrel



Discussion

We characterized the oceanographic and biological landscapes used by the SGP from Patagonian colonies during the breeding period. In general terms, our results announced the usage of an oceanographic scenario characterized by high productivity (eutrophic and enriched waters), warm SST (between 8 and 19°C), and shallow waters (neritics waters). SGPs from Isla Observatorio (southern colony) exploited marine areas of lower productivity and the sea surface temperature was cooler than birds from northern colonies. The higher proportion of time spent in eutrophic and enriched waters by giant petrels from the northern colonies could be linked to the presence of oceanographic fronts of high productivity nearby to the colonies, such as Valdes Peninsula, San Jorge Gulf, and coastal areas in the South of Argentina (Acha et al. 2004; Rivas et al. 2006). The Patagonian Shelf is extensively used as foraging

area for a large number and biomass of top predators who play key and varied roles in the marine ecosystem (Favero and Silva Rodriguez 2005; Falabella et al. 2009). Albatrosses, petrels, penguins, sea lions, and elephant seals are indicators of important coastal and pelagic marine areas, also highly significant for other marine animals. Its distribution is not uniform over the Patagonian Shelf with higher densities in those areas where the oceanographic characteristics promote prey concentration. Five satellite tracked species of albatrosses and petrels used marine pelagic areas of similar oceanographic characteristics as those used by the SGPs from Patagonian colonies such as the slope and the shelf-slope area at the latitude of the San Jorge Gulf (Arata et al. 2009; Quintana et al. 2009). Even tracked SGPs from South Georgia colonies used the Patagonian Shelf during their breeding and non-breeding season (González-Solís et al. 2008). None of those pelagic areas are under a regime of special management for the conservation

of biodiversity. However, to generate realistic habitat use maps for the SGP at the Patagonian Shelf, there is a urgency to track SGPs from Falkland Islands taking into account that the 40% of the global SGP population is located in these colonies (Patterson et al. 2008; Reid and Huin 2008) and there would be a potential overlap with the at-sea distribution of SGPs from Patagonia and South Georgia colonies.

In relation to the biological landscape, there was a high availability of food nearby colonies; which included an abundance of squid (at least in the northern colonies) as well as penguin and sea lion carrion. The temporal coexistence of the SGP breeding period and the potential carrion availability also emphasize the idea of a prosperous scenario to feed. While the chick-rearing period of the SGP goes from early January to late April (Copello and Quintana 2009a), Magellanic penguins hatch during November, the chicks remain in the colonies up to early February, and molting penguins (adults and juveniles) congregate at the coast up to late March (Schiavini et al. 2005). At the Patagonian rookeries, the sea lion pups born between December and February and yearlings leave their breeding sites in late April (Campagna 1985). In addition, the Southern Sea Lion have shown a population recovery in the Patagonian coast over the last few decades (Reyes et al. 1999; Dans et al. 2004), and penguin numbers have both increased and declined, depending on the colony (Schiavini et al. 2005). However, the penguin colonies located in the vicinities of the SGP northern colonies at the San Jorge Gulf showed increases in the number of breeding pairs during the last decade (Croxall et al. 2008). Such a prosperous foraging scenario may play a key role in the growth of the breeding population of SGP Patagonian colonies (Quintana et al. 2006). The same trend was also observed in Malvinas (Falkland) islands (Reid and Huin 2008) where breeding giant petrels probably face similar physical and biological marine landscapes to the Patagonian Shelf. Other pieces of evidence (gathered from the northern SGP colonies) to support the idea of a favorable foraging conditions were related with a constant high breeding performance reporting since 2001 breeding season (Quintana et al. 2006; Copello and Quintana 2009a, F. Quintana unpub. data) and with a high stability in the diet composition between 2001 and 2004 breeding seasons (Copello et al. 2008). The productivity of Patagonian Shelf areas for foraging seabirds was also suggested by Forero et al. (2004) who showed a high trophic overlap within the seabird community and suggested that the coexistence of this species could be interpreted as a consequence of a superabundance of food in the area.

In addition to the scenario described above, previous studies showed that the SGP population growth in Patagonia could be also consequence of the high surplus of food in form of discards from commercial fisheries. SGPs from

northern and southern colonies showed a high overlap with the operational areas of a huge trawler fleet (Copello and Quintana 2009b), and the species is one of the most frequent seabirds associated with these kind of vessels in the Patagonian Shelf (González Zevallos and Yorio 2006; Sullivan et al. 2006; Favero et al. 2010).

This study identified differences in the characterization of the habitat use by both sexes of SGP in Patagonian breeding colonies. Overall, females spent more time in the shelf break and exploited deeper waters than males. In contrast, males spent more time in coastal areas where potential high concentration of carrion is located, and they also showed a higher spatial overlap with areas of high squid density than females. This study supports the findings of previous studies carried on Subantarctic colonies where sexual segregation was reported in diet (Hunter 1983; Hunter and Brooke 1992), foraging behavior (González-Solís et al. 2002a), areas used at sea (González-Solís et al. 2008), and toxicity by metals (González-Solís et al. 2002b). More recent studies at the Patagonian colonies identified a clear sexual segregation in the trophic level of SGP from Arce and Gran Robredo colonies (Forero et al. 2005) and differences in the foraging strategies and marine habitat use of females and males (Quintana et al. 2010).

Finally, our increasing ability to understand individual and population-level spatial usage is timely, since a large proportion of pelagic seabirds (especially albatrosses and large petrels) are threatened by incidental mortality in long-line and trawl fisheries (Montevecchi 2002). Hence, knowledge of their habitat use and preferences will be critical for the monitoring and mitigation of these and other anthropogenic impacts on the marine environment. Future studies should evaluate which are the variables that determine the spatio-temporal distribution at sea of the SGP to therefore predict the distribution of the species in relation to their environment.

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