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# Tracking the exposure of a pelagic seabird to marine plastic pollution

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ABSTRACT

We aimed to describe how debris originated from coastal cities and fisheries circulates and accumulates along the Argentine continental shelf and its potential interaction with southern giant petrels (SGP, *Macronectes giganteus*). We used tracking data of 31 SGPs (adults and juveniles) from Patagonian colonies. Lagrangian simulations of particles were released from coastal cities and fisheries. Oceanographic features together with plastic input generated a corridor of debris through the Argentine shelf with areas of high debris accumulation, exposing SGP to plastic consumption. During chick provisioning trips 93.9% of petrel's locations overlapped with areas of plastic accumulation. Although early developmental stages were more exposed to particles from cities, the exposure of petrels (all classes) to debris from fisheries was 10% higher than from cities. Measures to reduce debris from fisheries, would reduce plastic ingestion by giant petrels. Proper management of open sky dumpsters would reduce plastic consumption by chicks and juveniles.

## 1. Introduction

Plastic pollution at sea is an emerging global environmental concern. Litter enters the ocean from different sources, the ocean based source that includes litter being lost, intentionally dumped, and/or discarded by commercial and artisanal fisheries, cargos or recreational boats; and the land-based source that includes general and accidental littering and landfills or dumpsters inadequately managed, increasing the risk of windblown litter reaching the ocean (Lambert et al., 2014). Approximately 80% of plastics in the ocean is estimated to come from land-based sources, and the remaining 20% would be provided by ocean based sources (Sheavly and Register, 2007; UNEP, 2021). Yearly, 4.8 to 12.7 million metric tons of plastics enter the ocean (Jambeck et al., 2015), and as it is mostly buoyant, it distributes, circulates, and accumulates being drifted by currents and winds (Eriksen et al., 2014). Concern on this issue increases when new discoveries determine that most of plastic that has entered the ocean by 1950s is still circulating between coastal environments, recurrently beaching, entangling, defouling, and resurfacing again (Lebreton et al., 2019) threatening marine megafauna that are at risk of entanglement, ingestion, or habitat degradation (Senko et al., 2020).

Albatrosses and large petrels are considered among the most threatened of all birds (Phillips et al., 2016) being the subject of anthropogenic hazards among which, plastic pollution is of main concern (Senko et al., 2020). Procellariiforms are wide ranging species, occupying vast pelagic environments, with most species foraging mainly at the sea surface, related to natural prey and in some cases related to fisheries discards, where most plastic accumulates; as a consequence they are the group of seabirds with the highest incidence of debris ingestion (Titmus and Hyrenbach, 2011; Roman et al., 2019). Several studies have demonstrated the presence of plastics circulating along the South Atlantic Ocean (Wilcox et al., 2015; Lebreton et al., 2019; Suaria et al., 2020) with considerable interaction such as entanglement or ingestion by albatrosses and petrels (Copello and Quintana, 2003; Petry et al., 2007; Jiménez et al., 2015; Dias et al., 2019; Phillips and Waluda, 2020).

The Argentine continental shelf (Southwestern Atlantic Ocean) is one of the global regions with most productivity (Allega et al., 2021). As

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marine fronts are abundant in the shelf, this area plays a key role in ecological processes generating an exceptionally high primary productivity (Acha et al., 2004) which congregates several species of seabirds, specially albatrosses and large petrels (Croxall and Wood, 2002; Favero and Silva Rodríguez, 2005; Arata et al., 2009; Quintana et al., 2009). The general circulation of the shelf is governed by a northward flow of cold waters (Malvinas current) and a southward warm water flow coming from the north (Brazilian current, Fig. 1a). These two currents collision is known as the Brazil/Malvinas confluence (Fig. 1a), highly influencing the ocean circulation over the shelf (Matano et al., 2010). Seasonal variations in the shelf are driven by wind forcing and by onshelf fluxes from the Drake Passage and from Malvinas/Falkland Islands (Combes and Matano, 2018). Moreover, the circulation of the San Jorge gulf (the largest gulf of the Argentine shelf) is mainly driven by wind and tidal forcing with seasonal variations and water intrusion from the Patagonian shelf (Palma et al., 2020).

The Southern Giant Petrel (*Macronectes giganteus*) is a wide range Procellariiform restricted to the Southern Ocean, that plays a key ecological role as scavenger and predator (Hunter, 1985; Techow et al., 2010). Global population shows an increase, although trends of individual populations are variable (BirdLife International, 2018). In coastal Patagonia Argentina, 80% of the breeding population occurs at the northern limit of the San Jorge gulf (Arce and Gran Robredo Islands). These islands are under protection by the Coastal and Marine Interjurisdictional Park Patagonia Austral, where 2300 breeding pairs occur (Quintana et al., 2006). Plastic consumption by this population has been well documented, as more than 70% of chicks from Arce and Robredo Islands contained some kind of plastic in their diet (Copello and Quintana, 2003). Moreover, juveniles and adults stranded on the colony or on nearby beaches contain plastic items in their stomach (Gallo et al. unpublished data). Nonetheless, the source and the areas where birds are getting debris remain unknown; consequently, the Southern Giant Petrel has become a good model to study the spatio-temporal interaction between plastic circulation of marine debris and pelagic seabirds. Understanding the relationship between the spatio-temporal at-sea distribution of seabirds and plastic debris is of paramount importance in determining high risk areas, and in contributing to the implementation of monitoring and mitigation measures for the species inhabiting the Argentine continental shelf and similar marine areas worldwide.

Although few studies estimated the densities of floating plastics offshore, in coastal surface waters, and beaches at remote islands on the South Atlantic Ocean (Lebreton et al., 2012; Eriksen et al., 2014; Barnes et al., 2018), studies modelling plastic debris circulation at regional (fine) scale are lacking. Likewise, there are no studies modelling transport and accumulation of floating debris in the continental shelf of Argentina. Hence, the goal of this study was to describe how marine debris coming from coastal cities and discarded by fisheries circulates and accumulates in the Argentine continental shelf and its potential spatio-temporal interaction with the at sea year-round distribution of the Southern Giant Petrel, depending on foraging strategy, sex, age classes, and breeding stage. As southern giant petrels have shown a strong interaction with fisheries discards as a foraging source along the year (Copello and Quintana, 2009b; Blanco et al., 2015) we hypothesize that this species will interact mainly with marine debris originated from fisheries operating in the area. Moreover, in concordance with previous studies (Copello and Quintana, 2003), petrels during chick provisioning trips will show a strong overlap with areas of high plastic accumulation.

## 2. Materials and methods

### 2.1. Southern Giant Petrel tracking data

For the present study we used tracking data of 24 southern giant petrels (11 breeding adults, six non-breeding adults, and seven juveniles) from previous studies (Quintana et al., 2010; Blanco and Quintana, 2014) derived from satellite transmitters (PTTs-100, “Platform Terminal Transmitters”, Microwave Telemetry, Columbia, MD, USA) from Arce (45°00′ S; 65°29′ W) and Gran Robredo Islands (45°80′ S; 66°03′ W, Supplementary Table 1). We also used a complementary set of new positional records derived from the instrumentation of seven adult breeders with GPS from Arce (Axy-Trek Remote, Technosmart, Italy, Supplementary Table 1). The foraging variables (i.e. distance to colony, total distance traveled, and trip duration) and the sexual segregation of breeding adults were determined only from new GPS records. However, both data sets (i.e. those from PTT and those from GPS units) were included to analyze the use of marine areas and its interaction with marine debris circulation for all bird classes (breeding, non-breeding (i.e. wintering) adults, and juveniles). Instrumented birds were sexed by

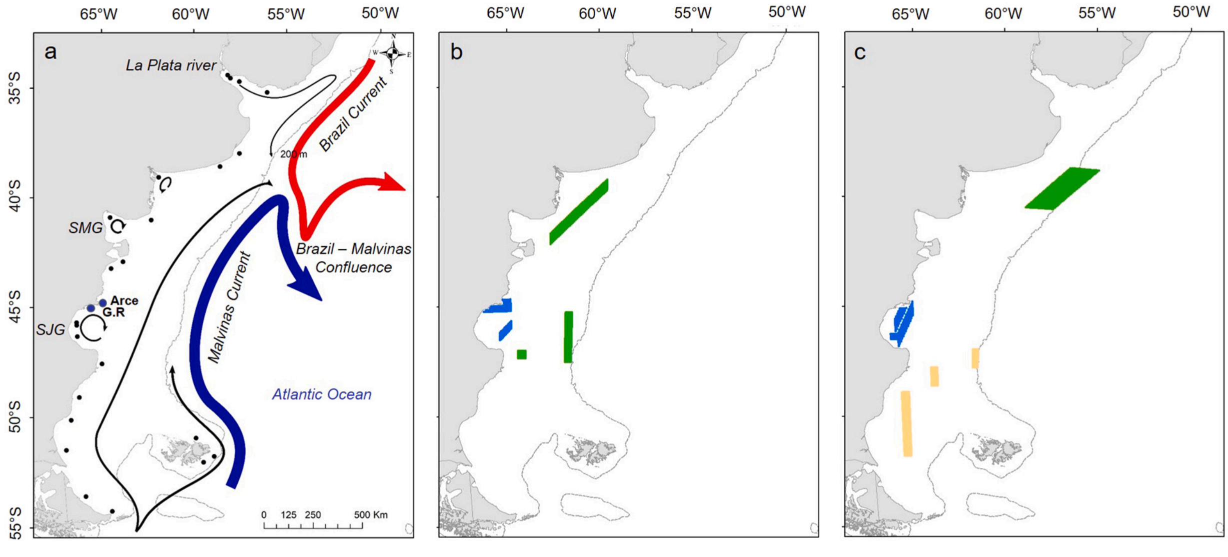

**Fig. 1.** Argentine shelf experiment. a) Schematic representation of coastal/shelf (black lines) and general (red and blue lines) circulation (from Matano et al., 2010). Particles released from coastal cities (black dots) on December 1st and June 1st. SMG: San Matías gulf, SJG: San Jorge gulf. Blue dots indicate locations of breeding colonies: Arce and Gran Robredo (G.R.) Islands; b) and c) Start points of inert particles (mimicking debris) discarded by fisheries on December 1st (b) and June 1st (c). Blue: double beam trawlers (target: shrimp), green: Ice trawlers (target: hake), yellow: Jiggers (target: squid). Distribution of fisheries was obtained from Góngora et al. (2012) and PAN-AVES (Santos, 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

morphometric measurements and/or by molecular techniques (Copello et al., 2006).

PTTs were attached using Tesa tape to the mid-dorsal mantle feathers (see Quintana et al. (2010) for details). Data on the geographic position of the PTT-instrumented animals were obtained from the ARGOS service provider (CLS, Toulouse, France). Each one of the obtained positions was automatically classified according to its estimated error (Argos-CLS, 2011). Argos satellite data was filtered using Argosfilter 0.62 Package for the R software package (R Development Core Team, 2019). Tracking data were then hourly resampled using the "*adehabitat*" package for R with "*redisltraj*" function (Calenge, 2006).

GPS loggers were attached to adult breeders during the early chick rearing period (i.e. early January) by using a leg loop harness (Mallory and Gilbert, 2008). The harness was build using 6 mm natural tubular Teflon tape. Each GPS unit was placed on a neoprene base (approximately 5 × 5 cm), to avoid friction between the logger and the skin of the bird, and then mounted on the harness. GPSs had a rechargeable battery with small solar cells and transmitted information to a base station placed on the colony (UHF data download up to 2 km). Loggers were programmed to collect location data every 10 min. The accuracy of GPS data (<10 m) allowed to discriminate between long and short trips (i.e. the dual foraging strategy previously described for breeding adults (Quintana et al., 2010)), which were analyzed separately. For each foraging trip, we calculated distance to colony, total distance traveled, and trip duration.

Additionally, at sea positions from both types of data loggers were classified as foraging (i.e. floating) or non-foraging (i.e. flying) locations, based on speed and turning angle between consecutive locations of each individual, following Blanco et al. (2015). Only locations classified as foraging were considered to study the spatio-temporal interaction of the birds with plastic debris circulation. Moreover, GPS data corresponding to long trips were resampled hourly, in order to make location from both devices comparable and ensuring that individual variation in daily transmission did not influence the spatial analysis. With the purpose of graphically describe areas highly used by different age/sex classes; we built a raster from the hourly resampled locations using the function "conversion tools", adding "count" as cell assignment type, with a resolution of 50 km.

### 2.2. Numerical models and set up of experiments

We employed four years (2000, 2001, 2004 and 2005) of hydrodynamical model outputs using Regional Ocean Model System (version ROMS-Agrif) previously tested in the region (Combes and Matano, 2018). ROMS-Agrif (Debreu et al., 2012) is a Regional Ocean Model System which use an adaptive method for running two or more embedded computational grid of different spatial resolution (parent-child grid). The numerical model was tested and validated in several regions of the world by the scientific community (https://www.myroms.org/ and https://www.croco-ocean.org/download/roms_agrif-project/). In the vertical, the model's primitive equations were discretized over variable topography using stretched terrain-following coordinates. In the horizontal, the primitive equations were evaluated using orthogonal curvilinear coordinates on a staggered Arakawa C-grid. The bottom topography was based on digitalized nautical charts. The model was forced at the open boundaries with M2 tidal component from the parent model. The model was forced at the surface with 3-day-averaged fluxes, wind speed, tidal forcing, and large scale fluxes at the open boundaries extracted from global and southern hemisphere models respectively (Combes and Matano, 2014). For more details about the hydrodynamical model and setup see Combes and Matano (2018).

The computational grid extend included a large part of the Southwest Atlantic Ocean (from 26° to 56° south latitude and from 69.2° to 46° west longitude, including the full extension of the Argentine continental shelf) and had a mean spatial resolution of 6.5 km. The covered area matched with previous studies of year-round at sea distribution of the Southern Giant Petrel (Blanco et al., 2017). The temporal resolution of the simulations (model outputs) was 10 days average.

### 2.3. Numerical experiments of inert particles

Using information of the region and understanding dynamics of giant petrels we designed a suite of Lagrangian simulations of particles (individual based model) using the Larval TRANSport Lagrangian model (LTRANS (North et al., 2006)). The LTRANS is an off-line particle-tracking model that runs with the stored predictions of a 3D hydrodynamic model. LTRANS is written in Fortran 90 and is designed to track the trajectories of particles in three dimensions. The simulations incorporated the main physical characteristics of the marine debris that reaches the regions of interest from coastal cities and main fisheries operating in the Argentine shelf. The Lagrangian simulations are based on the petrels' life stages. Five experiments (Supplementary Table 2) were carried out by initializing at two times of the year (austral spring and autumn) and for 180 days, each covering the circulation of particles for a complete annual cycle. The particle simulations were carried out considering the buoyancy of the inorganic material (marine plastic debris) without considering the vertical advection and movement only in superficial layers (as southern giant petrels are mainly surface feeders, (Croxall and Prince, 1980)). The results of inert particles experiments were recorded every 12 h (snapshot). Experiments were designed, without prior specific considerations, either due to lack of knowledge or complexity (amount of debris dumped in each city, frequency of debris release to the ocean, exact location of the fleets, etc.). Their focus was to present the minimum conditions for releasing debris at sea.

### 2.4. San Jorge gulf experiment

Inert particles (20 particles per computational node) were released on December 1st (running for 90 days) from inner San Jorge gulf (see Fig. 1a, Supplementary Table 2). Release locations of simulated particles were coincident with trawler fisheries (Argentine Red Shrimp, *Pleoticus muelleri*) operating in the gulf (Góngora et al., 2012). In addition, this simulation considered also debris coming from coastal cities located in the coast of the gulf. Ending points of the inert particles' trajectories were mapped at 35, 40, 45, 50, 55 and 60 days (20 × 20 km spatial resolution) temporally coincident with the Southern Giant Petrel chick rearing period at Arce and Gran Robredo Islands (Copello and Quintana, 2009a). To simulate a continuous system (as debris are being released to the ocean continuously) we overlapped all maps (from 35 to 60 days) accumulating the number of particles per pixel.

### 2.5. Argentine shelf experiments

The second and third experiments took into consideration the drifted particles originated in coastal cities (Supplementary Table 2). These experiments were released on December 1st and June 1st (each running for 180 days) from 20 coastal Argentine cities and from 3 locations in Malvinas/Falkland Islands, with 100 inert particles released in each computational node representing each city (Supplementary Table 2, Fig. 1a). In those cities, open sky dumpsters are located on the coastline and predominantly westerly winds (Palma et al., 2004) blow part of the debris to the ocean. Moreover, in the fourth and fifth experiments (Supplementary Table 2), drifted particles originated from fisheries (from discards or debris that is thrown to the ocean). These particles were released on December 1st and June 1st (running each for 180 days) in concordance with main fisheries operating at the study area. Main locations of operation of Argentine Hake (*Merluccius hubbsi*) fishery (high-seas ice trawler fleet), Argentine Short Fin Squid (*Illex argentinus*) fishery (jigger fleet), and Red Shrimp fishery (double-beam trawler fleet) were mapped following Góngora et al. (2012) and PAN-AVES (Santos, 2010) to define the start points of simulated particles (Fig. 1b, c).

End points of particles from each model were obtained at 60, 90, 120, 150, and 180 days. In order to simulate a continuous drift of particles, we plotted all end points from each model and then rasterized positions at 50 × 50 km spatial resolution using ArcGis. The raster was built with the function "conversion tools", using "count" as cell assignment type. Therefore each cell obtained the total number of particles (at 60–180 days) allocated by the model.

In order to assign a value to each petrel location, we overlapped temporally and spatially the foraging locations for all tracked birds with the corresponding model and assigned a value of inert particles to each location, resulting in interaction values (0 = location did not interact with a pixel with particles; 1 = location interacted with a pixel with particles) and the number of particles per location.

### 2.6. *Statistical analysis*

General mixed effect models (GLMM) were used to test differences between sexes for trip duration, maximum distance to colony, and total distance traveled (calculated from GPS data). Individual models were carried out separately for (1) short and (2) long foraging trips, sex was included as a fixed factor and bird identity as a random factor to account for potential pseudoreplication (Crawley, 2007; Zuur et al., 2009). Additionally, we obtained a mean value per variable per individual. Then, we used these mean values to calculate a grand mean per sex and its standard deviation. Values through the text are expressed as mean ± standard deviation.

To analyze the variability of the response variables, "interaction with debris" (binary variable: no interaction/interaction with inert particle) and "number of particles per location" (considering only locations with interaction), we used GLMM with "bird identity" as a random factor (Crawley, 2007; Zuur et al., 2009). Binomial family distribution and logit-link function were employed for models with "interaction with debris" as response variable. For models with "number of particles per location", we used GLMMs with Poisson errors and log-link function to deal with non-Gaussian distributions (Crawley, 2007). These analyses were performed for each source of debris (cities and fisheries), considering three datasets: (1) breeding adults, (2) breeding and non-breeding (wintering) adults, (3) non-breeding adults and juveniles. In models including dataset for breeding adults (1 and 2), we considered sex as fixed factor, as sexual spatial segregation occurs during breeding (Quintana et al., 2010). In models considering datasets 2 and 3, "bird class" (breeding adult, non-breeding adult, and juvenile) was included as explanatory variable. In addition, for each bird class, GLMMs were performed to analyze differences in response variables according to type of fishery (ice trawlers, jiggers, and double-beam trawlers).

GLMMs were run using the function *lmer* from the package *lme4*. Explanatory variables included in the models were evaluated with the function *anova* using the Chi-square test goodness of fit ($\chi^2$ parameter). All statistical analyses were performed using the open source statistical package R version 3.6.1 (R Development Core Team, 2019) with a level of significance of $P < 0.05$. Data for "interaction with debris" (frequency of occurrence, %) and "number of particles per location" (mean ± standard deviation) were expressed by bird class, source of debris, and sex (only for breeding adults).

## 3. Results

### 3.1. *Foraging trips and sexual segregation*

Similarly to previous findings from this population (see Quintana et al., 2010), data from the birds tracked with GPS units showed a dual foraging strategy (i.e. short and long trips). Short trips were statistically similar for females and males, and were performed in coastal areas at 38.5 ± 12.9 km from the colony and adult breeders traveled a mean distance of 98.7 ± 38.8 km per trip during 7.1 ± 1.0 h (Supplementary Tables 3, 4).

Long trips were also similar for female and male breeders, although females reached slightly more distant waters (486.0 ± 57.5 vs. 382.9 ± 65.1 km) and, consequently, traveled for slightly longer distances than males (2078.3 ± 333.7 vs. 1741.0 ± 522.3 km) (Supplementary Tables 3, 4). As previously described for the same population (Quintana et al., 2010), GPS data also showed a clear sexual segregation in the use of the foraging areas during the breeding period. While males foraged in coastal areas, females used pelagic waters on the middle shelf and the shelf break (Supplementary Fig. 1).

### 3.2. *Use of marine areas*

During the breeding period adults foraged in an area that extended from 40°S in the north to 50°S to the south, and to the shelf break to the west. High used areas were mainly a coastal area from the breeding colony to approximately 350 km to the north, and an area comprising the middle shelf and the shelf break located at approximately 450 km from the colony (Supplementary Fig. 2a, see also Quintana et al. (2010)).

During winter, adults stayed within the Argentine continental shelf exploiting coastal, middle shelf, and shelf break waters expanding up to 840 km from the colony to the north and 960 km to the south. Non-breeding adults alternated at sea excursion with periods at the colony (Supplementary Fig. 2b, see also Blanco and Quintana (2014)). On the other hand, first year juveniles during their first incursion at sea occupied an extensive area, on which they explored a corridor between the colony and the middle shelf, the shelf break, an area comprised between the Argentinian and the Uruguayan shelf, and a south Brazilian shelf area (Supplementary Fig. 2c, see also Blanco and Quintana (2014)).

### 3.3. *Hydrodynamical model*

There is enough published information on the performance of this model to trust the results of the tracking experiments of plastic debris. Further description of the model, including comparison with in-situ and satellite observations, is presented in Combes and Matano (2014, 2018, 2019), Matano et al. (2014), Strub et al. (2015), Franco et al. (2018), and Guihou et al. (2020). We present here the main characteristics of the surface circulation of the Southwestern Atlantic Ocean. The sea surface velocities (vectors, shown in Supplementary Fig. 3) indicated that the model is capable to generate the main circulations patterns of the Southwestern Atlantic Shelf, including the Malvinas Current, the Brazil Current, and their Confluence offshore La Plata river mouth. The higher values of SST gradient (red contours, shown in Supplementary Fig. 3) are associated with the position of the main thermal fronts in the Argentine shelf and other areas of high biological productivity (i.e. Valdes thermal front, San Matias gulf front, San Jorge gulf front, and shelf break front).

### 3.4. *San Jorge gulf experiment*

Movement of inert particles from coastal cities and the shrimp fishery inside the San Jorge gulf was a mixture of the summer cyclonic circulation typical of the gulf (Palma et al., 2020) and the prevailing winds in the region (Palma et al., 2004). The particles were transported in the surface layer, where the west wind is the predominant forcing (Ekman layer) and interacts with cyclonic circulation (intermediate layers) governed by the stratification and tide, moving the particles through the gulf from South to North. The temporal evolution of the particle density indicated that the first zone to displace the particles is the western coastal zone of the gulf, generating a concentration of particles in the mouth and north of the gulf (Fig. 2). This trend intensified around 40 and 50 days, where values quadrupled from the beginning reaching the vicinity of Arce and Gran Robredo Islands (Fig. 2). After 60 days, the particles almost completely left the gulf and a large concentration of particles moved in a NE direction over the shelf (Fig. 2). Interestingly, the particles accumulated in areas highly

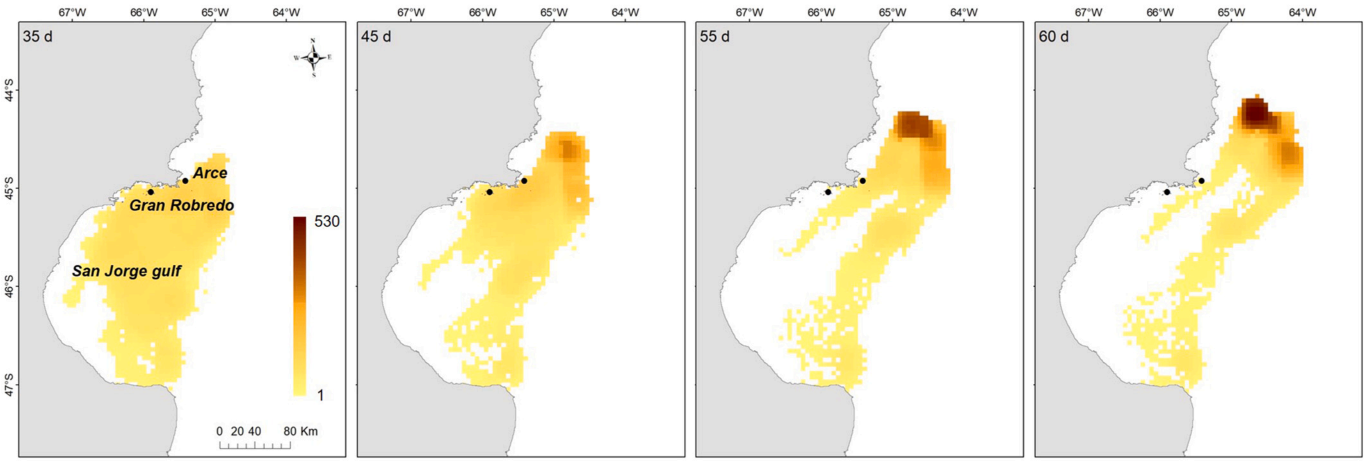

**Fig. 2.** San Jorge gulf experiment. Distribution and accumulation of inert particles (mimicking plastic) at 35, 45, 55, and 60 days after release. Particles were released simulating debris coming from coastal cities and fisheries operating inside the gulf. Scale represents number of particles per pixel (spatial resolution of 20 × 20 km).

exploited by male and female foraging southern giant petrels carrying out short trips from their breeding sites. As such, 93.9% of petrel's foraging locations overlapped with areas with particle accumulation, and the foraging birds mainly visited marine areas containing a mean of 112.5 ± 1.5 (range 24–420) particles per location (Fig. 3).

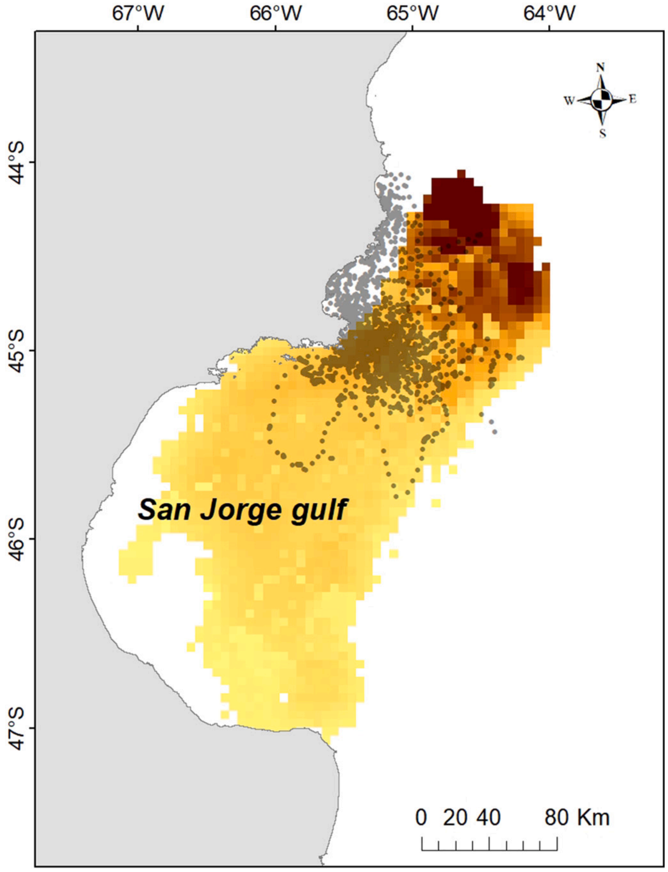

**Fig. 3.** San Jorge gulf experiment. At-sea distribution (grey dots) of foraging southern giant petrels carrying out short trips from Isla Arce (black dot) during the breeding period; in relation to the modelled accumulation of inert particles (simulating plastics) circulating for 60 days, released from coastal cities and fisheries operating inside the gulf. Scale represents number of particles (spatial resolution of 20 × 20 km).

### 3.5. *Argentine shelf experiments*

Overall, 32.9% of year-round at-sea foraging locations of the giant petrels overlapped with marine areas containing particles coming from coastal cities, and 43.6% with those delivered by fisheries operating in the Argentine continental shelf (Table 1).

#### 3.5.1. *Debris from cities*

Particles released from cities during austral spring mainly followed a NE direction of transport on the shelf (Fig. 4a), with the exception of those from the San Matías gulf, El Rincón (Bahía Blanca estuary), and La Plata river (Buenos Aires and La Plata cities, Fig. 4a). These specific particles faced a closed circulation dynamics that prevented the transport to the open shelf. After approximately 90 days, particles from La Plata River were pushed out to feed the Brazil/Malvinas confluence. The main contribution of particles into the continental shelf seemed to come from a particle retention zone generated in front of the San Jorge gulf, which could also have been contributing in part to the accumulation on shelf break (Fig. 4a). The cities of Ushuaia and Río Grande contributed material from their waste to the Malvinas/Falkland Islands region (Fig. 4a). The particles released from the North and East of Malvinas/Falkland Islands were captured directly by the Malvinas current that surrounds the Islands, contributing afterwards northward to the confluence zone to be later expelled offshore.

Overall, the 34.2% of at-sea foraging locations of breeding petrels (spring-summer) overlapped with marine areas containing particles coming from coastal cities (Table 1). As mentioned before, the spatial sexual segregation was notable during foraging excursions and, as a consequence, breeding females were partially more exposed to particles coming from cities than males (44.3 vs. 22.5% respectively Tables 1, 2; Fig. 5a, b). Nonetheless, males used marine areas with higher debris accumulation (249.5 ± 404.6 vs. 61.2 ± 171.9 particles/location for males and females respectively, Tables 1, 2).

Particles released from cities during austral autumn (Fig. 4b), showed similar trajectories that those during spring, with two exceptions: i) the displacement speeds were lower, and ii) the coastal circulation offered less retention. A clear evidence of this is showed in Fig. 4b: i) the particles launched in southern Patagonian cities (i.e. Ushuaia and Río Grande) did not reach the coast of Malvinas/Falkland Islands and ii) the San Matías gulf did not retain particles in its interior. It is important to mention that in coastal regions with a complex bottom or coastline shape, the particles can go to land or remain trapped in very shallow sectors (prevailing wind or circulation). In those cases, such as the San Matías gulf or El Rincón (Fig. 4b), the trajectory of some particles ended

**Table 1**

Percentage of Southern Giant Petrel's foraging locations that overlap with pixels containing inert particles originated from different sources. Particles/location indicates the number of particles accumulated per pixel (mean ± SD) corresponding to each petrel location. Values in bold indicate statistical significant differences.

| | Breeding adults | | | Wintering adults | Juveniles | All classes |
|---|---|---|---|---|---|---|
| | Male | Female | Total | | | |
| Debris from cities | | | | | | |
| Interaction (%) | 22.53 | 44.28 | 34.24 | **21.17** | **42.2** | 32.86 |
| Particles/location | **249.5 ± 404.6** | **61.2 ± 171.9** | 127.1 ± 290.6 | 40.7 ± 47.0 | 49.2 ± 69.7 | 103.11 ± 248.49 |
| Debris from all fisheries | | | | | | |
| Interaction (%) | 49.69 | 40.95 | 45.44 | 43.24 | 35.75 | 43.64 |
| Particles/location | 44.4 ± 60.0 | 64.9 ± 59.8 | 53.4 ± 60.8 | 87.4 ± 72.0 | 90.0 ± 87.6 | 61.58 ± 66.79 |
| Debris from ice trawlers (Target: Hake) | | | | | | |
| Interaction (%) | 5.55 | 20.34 | **12.32** | **0** | **2.52** | 7.74 |
| Particles/location | 28.0 ± 23.5 | 31.5 ± 22.0 | **31.9 ± 21.9** | – | **10.0 ± 11.7** | 30.1 ± 22.4 |
| Debris from jiggers (target: squid) | | | | | | |
| Interaction (%) | – | – | – | **31.81** | **9.26** | 28.30 |
| Particles/location | – | – | – | 84.2 ± 61.6 | **87.5 ± 88.4** | 90.4 ± 64.4 |
| Debris from double-beam trawler (target: shrimp) | | | | | | |
| Interaction (%) | 34.23 | 24.35 | **29.48** | **10.43** | **23.16** | 24.88 |
| Particles/location | 59.3 ± 66.4 | 85.7 ± 73.5 | **75.9 ± 72.3** | 97.6 ± 81.6 | **85.6 ± 73.6** | 67.0 ± 70.6 |

early. Moreover, the confluence zone expelled the particles to a more southerly direction, indicating less dispersion in offshore zones.

Wintering (non-breeding) and breeding adults showed similar interaction with drifted particles derived from coastal cities (Tables 1, 2). The apparent lower exposure of wintering adults to higher plastic concentration areas (40.7 ± 47.0 vs. 127.1 ± 290.6, Table 1) was not statistically significant (Table 2) probably due to a higher variability in the exposure to particles' accumulation by breeding adults (range: 1–1000 vs. 1–313 particles per location, for breeding and non-breeding adults respectively).

Juveniles were more exposed to particles coming from cities than wintering adults (42.2 and 21.2% respectively, Fig. 5c, d). However, both age classes were similarly exposed to the accumulation of drifted plastic (Tables 1, 2; Fig. 5c, d).

### 3.5.2. *Debris from fisheries*

During austral spring and summer simulated particles originated from operating commercial fisheries (jiggers did not operate at this part of the year) were transported towards NE over the shelf and followed the spring/summer typical coastal dynamics of the San Jorge gulf and Peninsula Valdés (Fig. 4c). The southern zone of the San Jorge gulf was feed by particles that were discarded into its mouth and then transported in a cyclonic direction through the gulf. Also, some particles to the south of the gulf were expelled in a NE direction towards the shelf break. The particles launched to the north of the San Jorge gulf traveled NE and feed the coastal platform reaching the isobath of 200 m (Fig. 4c). Moreover, at Peninsula Valdés, coastal particles were retained by an anticyclonic closed gyre previously reported (Tonini et al., 2013).

Overall, the 45.4% of at-sea foraging locations of breeding petrels (spring-summer) overlapped with marine areas containing particles coming from all fisheries (Table 1). Breeding males and females showed a similar overlapped and exposure to particles' accumulation originated from the fishing fleet (Tables 1, 2; Fig. 6a, b). Clearly, the main source of plastic debris during spring and summer came from the double-beam trawlers. The dynamic of simulated plastic delivered from the shrimp fishery produced the highest interaction between the areas used by breeding adults (29.5%) with an accumulation of 75.9 ± 72.3 particles per location (Table 3). Debris originated from ice trawlers interacted with only 12.3% of the breeding adults' locations which faced a lower accumulation of particles (31.9 ± 21.9 particles per location; Tables 1, 3; Fig. 6a, b).

Simulations of fisheries' debris launched in austral autumn indicated that particles displacement was slightly slower than in spring-summer. The particles mimicking discards from shrimp fisheries (double-beam trawlers) moved in a NE direction towards the shelf break (Fig. 4d). The southern gyre and the north section of the San Jorge gulf did capture a few particles, which were then unified in the direction of the rest (Fig. 4d). The exposure of wintering adults to mimicked plastic discarded by all fleets was similar to the exposure experienced by breeding adults (Tables 1, 2), as was the accumulation of particles experienced by both bird classes (Tables 1, 2). Moreover, wintering adults and juveniles experienced a similar level of exposure to plastic debris derived from fisheries and their foraging areas also showed a similar accumulation of particles (Tables 1, 2; Fig. 6c, d).

The debris originated from jiggers' fleet off Bahía Grande moved slowly to the north, reaching the shelf break from where they were quickly transported north bordering the shelf break (Fig. 4d). Those debris interacted the most with non-breeding adults (Fig. 6c) and were almost exclusively encountered by this bird class (i.e. 31.8% of its locations showed some interaction with debris versus only 10.4% originated in double-beam trawlers with no interaction with ice trawlers (Tables 1,3)). Nonetheless, accumulation of particles originated by jiggers and double beam trawlers experienced by wintering adults was similar (Tables 1, 3). Foraging juveniles were mainly exposed to simulated plastic released from double-beam trawlers, showing less interaction with plastic derived from jiggers and ice-trawlers (23.2, 9.3, and 2.5% respectively; Tables 1, 3; Fig. 6d). However, juveniles encountered areas with higher debris accumulation originated from jiggers and double beam-trawlers in contrast to lower accumulation of simulated particles released by the hake fishery (87.5 ± 88.4 and 85.6 ± 73.6 vs. 10.0 ± 11.7 particles per location respectively; Tables 1, 3).

## 4. Discussion

In this study, we modelled for the first time, floating plastic debris circulation and accumulation on the Argentine continental shelf at small and mesoscales. We also evaluated the spatio-temporal interaction of plastics, originated from land and ocean based sources, with the at sea year-round distribution of the Southern Giant Petrel, depending on foraging strategy, sex, age classes, and breeding stage. In general, our findings showed that shrimp and squid fisheries might cause the highest interaction between petrels and marine debris considering all analyzed

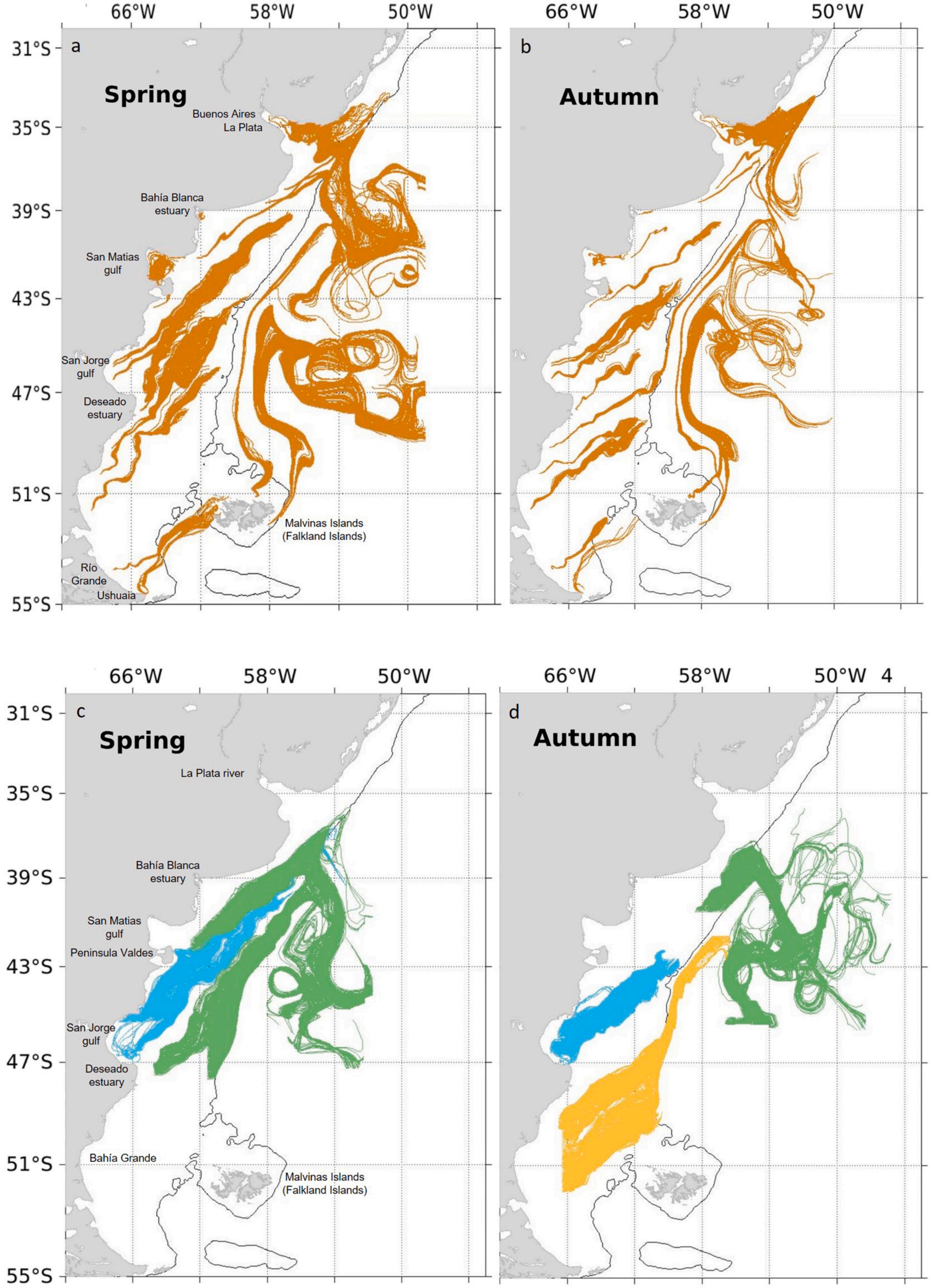

**Fig. 4.** Argentine shelf experiment. Trajectory of drifted particles (mimicking plastic) circulation at sea originated from coastal cities at December 1st (a) and June 1st (b) and discarded by fisheries at December 1st (c) and June 1st (d). Drifted particles run for 180 days after initial released. Type of fishery is indicated by colors: Double beam trawlers (target: shrimp) (blue), Ice trawlers (target: hake) (green), and Jiggers (target: squid) (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

classes. In addition, simulated plastic originated from cities demonstrated to be the main source of debris threatening petrels at their early life stages (chicks and juveniles). As demonstrated by our results, we aimed to approach an emerging global conservation issue to understand how the behavioral patterns of a pelagic seabird would influence the risk of plastic ingestion or entanglement. It also contributed to add information on the sources, transport, and accumulation of plastics, previously defined as research priorities (Vegter et al., 2014).

### 4.1. Plastic debris circulation at sea and the spatio-temporal interaction with foraging petrels

#### 4.1.1. Argentine shelf experiments

In general terms, plastics originated from cities were transported NE

**Table 2**
Results from GLMM performed for each source of debris (cities and fisheries), considering three datasets: (1) breeding adults, (2) breeding and non-breeding (wintering) adults, (3) non-breeding adults and juveniles.

| | Interaction (%) | Particles/location |
|---|---|---|
| Debris from cities | | |
| Male vs. female | $\chi_1^2 = 3.67$, $P = 0.05$ | $\chi_1^2 = 3.86$, P = 0.05 |
| Breeding adults vs. wintering adults | $\chi_1^2 = 0.18$, $P = 0.67$ | $\chi_1^2 = 1.32$, $P = 0.25$ |
| Wintering adults vs. juveniles | $\chi_1^2 = 5.16$, P = 0.02 | $\chi_1^2 = 0.004$, $P = 0.95$ |
| | | |
| Debris from fisheries | | |
| Male vs. female | $\chi_1^2 = 0.003$, $P = 0.96$ | $\chi_1^2 = 0.05$, $P = 0.81$ |
| Breeding adults vs. wintering adults | $\chi_1^2 = 40.179$, $P = 0.99$ | $\chi_1^2 = 4101.1$, $P = 0.68$ |
| Wintering adults vs. juveniles | $\chi_1^2 = 0.1$, $P = 0.75$ | $\chi_1^2 = 0.68$, $P = 0.41$ |

on the shelf, although retention in specific areas such as the San Jorge and San Matías gulfs, as a result of its closed summer circulation (Tonini et al., 2013), would increase debris accumulation. Debris discarded by commercial fisheries also followed the same NE destination to deeper areas, bordering the shelf break (200 m isobath) on the outer side and increasing the density of particles in that area. There was a clear difference in speed regimes in the particles that were transported in the most coastal areas up to the shelf break and the particles that reached the deepest offshore areas, since they were captured by the Malvinas current (Palma et al., 2008; Combes and Matano, 2018). A similar pattern was hypothesized for global circulation of plastics, being the "newer" debris captured by coastal waters, while the older items were found offshore (Lebreton et al., 2019). As indicated by the numerical experiments, most of the mimicked plastics from land and ocean based sources were destined to be captured by the Brazil-Malvinas confluence, which is responsible for expelling them offshore off the South American continent. In concordance with our results, high densities of marine debris were previously described for the Southwest Atlantic, where in some areas, more than 1000 items/km$^2$ were found floating at sea (Barnes et al., 2009). The above mentioned oceanographic features together with the plastic input from cities and fisheries generated: 1) a constant corridor of marine debris through the Argentine continental shelf, and 2) areas of high debris accumulation (reaching up to 1000 mimicked plastic each 2500 km$^2$), exposing giant petrels (all bird classes studied) to the risk of entanglement and/or plastic ingestion.

Overall, 32.9% of foraging locations of giant petrels overlapped with marine plastic debris originated from coastal cities, and 43.6% with those delivered by commercial fisheries. The dominant westerly winds of Patagonia (Palma et al., 2004) blow waste from more than 50 open sky dumpsters located on the coastline of Argentina (of a total of 5000 distributed along the country: www.argentina.gob.ar/ambiente) into the ocean. Additionally, commercial fisheries operating in the Argentine continental shelf discard waste thrown overboard that, together with hake discard (Dato et al., 2006; Góngora et al., 2012), attract several seabirds species including the Southern Giant Petrel (González-Zevallos and Yorio, 2006; Favero et al., 2011).

Sexual segregation during the breeding period is noticeable, with males foraging mainly along the coast associated to penguin colonies and sea lion rockeries, while females exploit high productive pelagic environments along the Argentine shelf and the shelf break (Copello et al., 2011). These differences exposed breeding adults slightly different to simulated plastic originated from cities, while females interacted in almost 45% of their locations with plastics, males foraged in areas with the highest particles' accumulation. Although this could have indicated that males had less interaction with plastics, areas with high densities of debris also represented a threat for this group, as encounter density could be an important driver of the incidence of debris ingestion, when compared with less polluted areas (Van Franeker and Law, 2015; Roman et al., 2019). Juveniles during their first incursion at sea faced the highest interaction with debris coming from cities when compared to wintering adults, as they move NE, following a corridor along the shelf (Blanco et al., 2015) that overlapped with the marine debris corridor that constantly circulated along the Argentine continental shelf. Despite of the at sea behavioral differences above mentioned, all bird classes interacted similarly with debris originated by all fisheries. The exposure of petrels to debris originated from fisheries was 10% higher than the exposure of debris originated from cities. Giant petrels are largely known to interact with fishing vessels along the year (Copello et al., 2011; Blanco et al., 2015; Krüger et al., 2017; Phillips and Waluda, 2020). Shrimp fisheries (one of the main sources of discards of the Argentine sea (Góngora et al., 2012; Marinao et al., 2014)) seem to be the main source of plastic debris responsible for interaction with breeding adults and juveniles, producing also high accumulation areas of marine debris, coincident with the areas exploited by all bird classes along the year. During winter, adults showed a high interaction with debris originated from jiggers; which goes in concordance with previous records of the spatial overlap between non-breeding foraging petrels and this fleet (Blanco et al., 2015; Krüger et al., 2017). The overlap of juveniles with debris from jiggers was lower, probably due to the low interaction of this age class and fishing vessels (Blanco et al., 2017; Weimerskirch et al., 2020). However, the circulation of debris originated on this fleet ended up accumulating in areas highly exploited by juveniles. Nonetheless, caution must be taken when interpreting these results, as the interaction with debris coming from fishing vessels may be higher than what is modelled in this study. Giant petrels forage directly on fisheries discards and on waste thrown overboard when it is occurring (Favero et al., 2003), which would increase their risk of ingesting plastic (Phillips and Waluda, 2020). Likewise, here we simulated one time of release particles aiming to understand debris circulation, while in reality there is a continuous contribution of debris from fisheries and cities that could also lead to an underestimation of the interaction between petrels and debris presented in this study.

### 4.1.2. *San Jorge gulf experiment*

The movement of particles mimicking plastics originated from shrimp fisheries and cities inside the San Jorge gulf, responded to the typical circulation of the gulf and to the prevailing westerly winds that characterize the region (Palma et al., 2004). Features of some sections of the gulf with shallow depths and areas where the tide generates a mixing from surface to depth (Palma et al., 2020) noticeably influenced displacement of particles, as they moved slowly when compared to regions where wind governs the transport. Moreover, when the particles encountered retention zones (such as strong closed gyres, areas of high mixing or thermal fronts) in their free movement they began to concentrate, increasing their density in a smaller area and moving together. This drove particles, to accumulate right to the north of the Giant Petrel's breeding colonies coincident with the area highly occupied by this species while carrying out chick provisioning trips (i.e. short trips). As breeding Procellariiforms are not able to replenish their own body reserves and maintain chick development in areas of low productivity surrounding the colonies, they adopted a dual foraging strategy to overcome this limitation (Weimerskirch, 1998). This strategy resides in the fact that they alternate long trips, getting food for themselves to improve body condition with short (near colony) foraging trips, in which they obtain little amounts of food, satisfying chick requirements (Weimerskirch, 1998; Congdon et al., 2005). During chick provisioning trips, adults explored waters neighboring the colony occupying the north of the San Jorge gulf. As a consequence, more than 90% of petrels' locations overlapped with areas of particles accumulation being the stage with higher risk of interaction with plastic debris. These results are supported by the amount of plastics encountered in chicks' diet from the same population (more than 70% of food samples contained marine debris (Copello and Quintana, 2003; Copello et al., 2008)). Intergenerational plastic transfer from adults to chicks through regurgitation is usual in albatrosses and petrels (Carey, 2011; Rodríguez et al., 2012;

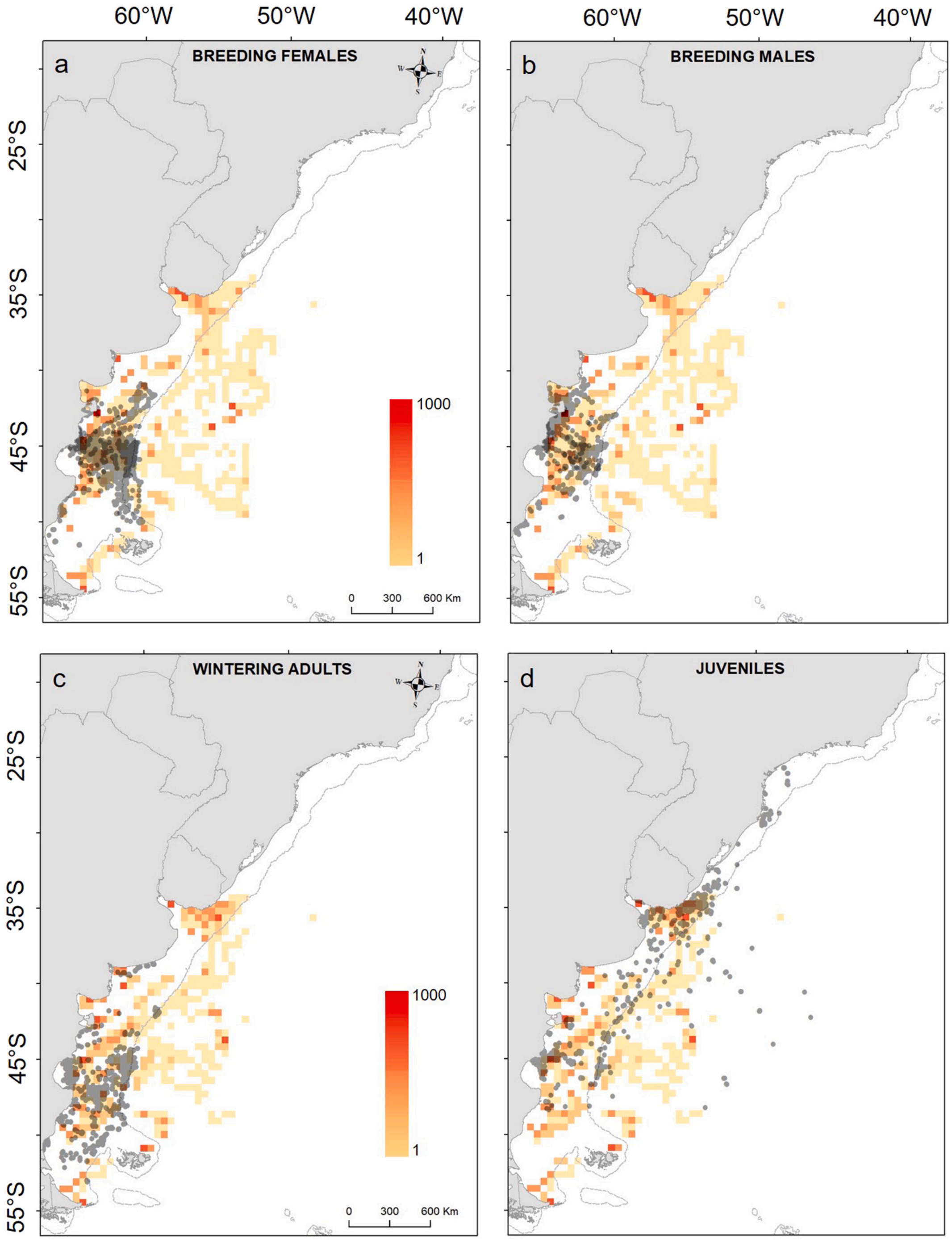

**Fig. 5.** Argentine shelf experiment. At-sea distribution (grey dots) of foraging adults and juveniles Southern Giant Petrel along the year; in relation to the modelled accumulation of inert particles (simulating plastics) released from coastal cities at December 1st (a) and (b) and June 1st (c) and (d). Each pixel (spatial resolution of 50 × 50 km) represents the aggregated total number of particles accumulated at 60, 90, 120, 150, and 180 days since release. Scale represents number of particles.

Jambeck et al., 2015; Ryan, 2015; Hyrenbach et al., 2017). Procellariiforms concentrate oil in their proventriculus, as a mechanism to reduce the mass and frequency of meal delivered to chicks, decreasing therefore the time and energy costs involved in transporting food (Connan et al., 2005). The plastic items collected by adults during short trips, could increase mass of meal and consequently the cost of transport. Additionally those plastic items will be transferred to chicks, increasing the risk of gut obstruction, or even reducing the desire of feeding by causing a false perception of satiation (dietary dilution), leading to malnutrition (Senko et al., 2020). This persistent plastic ingestion may alter the dynamics of this population as physical condition in early developmental stages (i.e. low mass at fledging (Auman et al., 1997)) could have a detrimental effect on juvenile survival (Lindström, 1999; Morrison et al., 2009).

### 4.2. *Final considerations*

Overall, southern giant petrels (i.e. all sex and age categories) seem to be highly exposed to marine plastic debris delivered by both coastal cities and commercial fisheries operating at the Argentine continental shelf. The exposure of foraging birds to high plastic accumulation areas was evident, reaching values of more than 1000 particles per 2500 km$^2$.

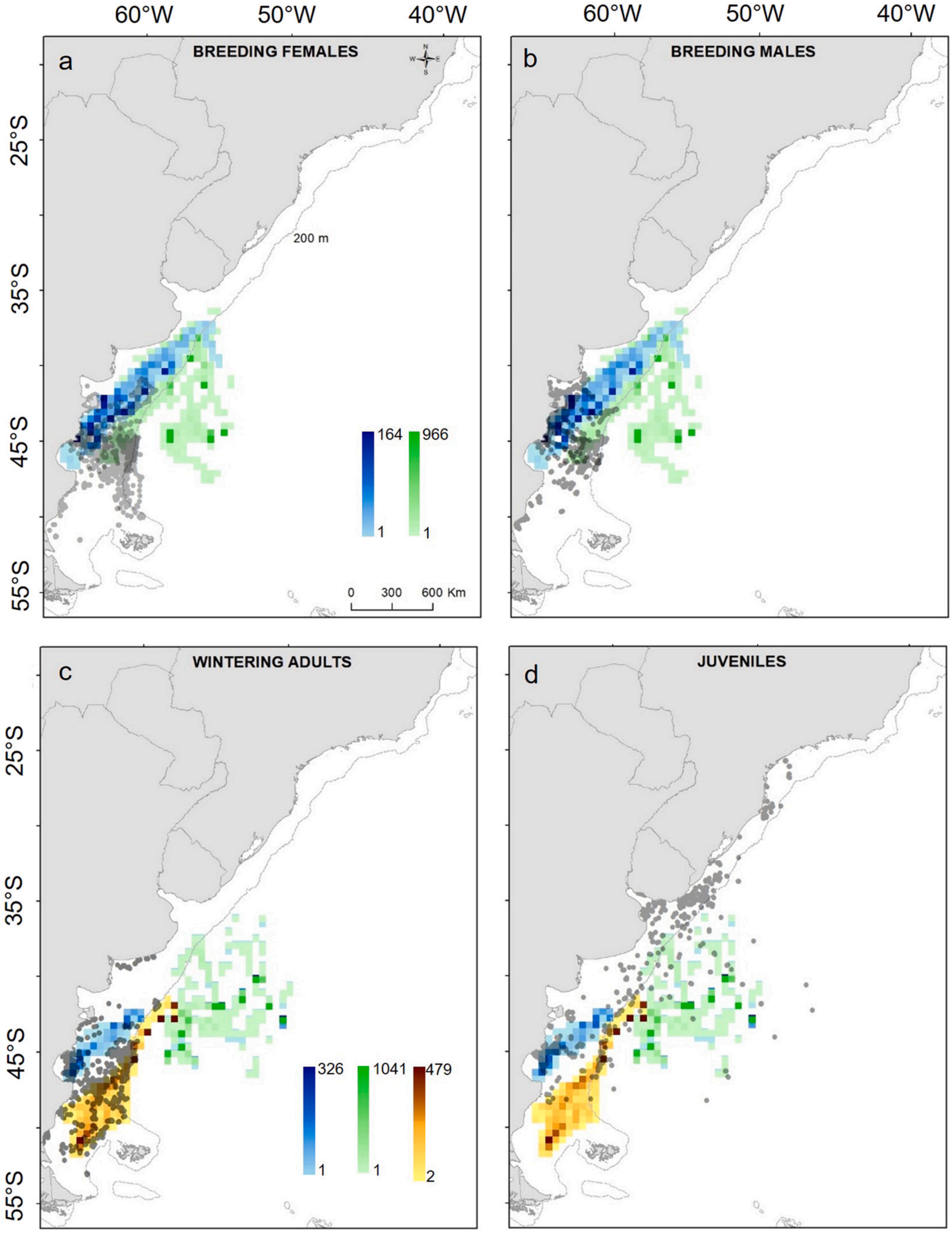

**Fig. 6.** Argentine shelf experiment. At-sea distribution (grey dots) of foraging adults and juveniles Southern Giant Petrel along the year; in relation to the modelled accumulation of inert particles (simulating plastics) released from fisheries at December 1st (a) and (b) and June 1st (c) and (d). Each pixel (spatial resolution of 50 × 50 km) represents the aggregated total number of particles accumulated at 60, 90, 120, 150, and 180 days since release. Scale represents number of particles. Type of fishery is indicated by colors: Double Beam Trawlers (target: shrimp) (blue), Ice Trawlers (target: hake) (green), and Jiggers (target: squid) (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The chronic and sublethal effects of plastic ingestion in seabirds could cause starvation (Pierce et al., 2004), reduce body mass, affect body condition, reduce size of chicks (Lavers et al., 2014; Lavers et al., 2019), decrease fat deposition (Auman et al., 1997), and change blood chemistries associated with dietary deficiencies, influencing population dynamics (Lavers et al., 2019). It was previously indicated that most of plastic ingested by seabirds could be predicted based on ecological features (i.e. body size, foraging strategies) and on the exposure of these birds to highly polluted areas (Van Franeker and Law, 2015; Wilcox et al., 2015; Roman et al., 2019). As revealed by our simulations, the risk of exposure to plastics by giant petrels depends on bird classes and on the source of marine debris. Even though population trends of the Southern Giant Petrel in Arce and Gran Robredo Islands remain stable (Quintana et al., 2006; Quintana and Blanco unpublished data) the imminent increase of plastics circulating in the ocean (Hammer et al., 2012; UNEP, 2021) and the potential negative effects of plastic ingestion in seabirds (Lavers et al., 2019; Prokić et al., 2019; Puskic et al., 2020), could modify this trend. At a population-level, adult survival is key for population growth (Jenouvrier et al., 2005). The fact that males and females interacted slightly differently with debris, could lead (as this

**Table 3**
Results from GLMM performed for each bird class according to type of fishery (ice trawlers, jiggers, and double-beam trawlers).

| | Interaction (%) | Particles/location |
|---|---|---|
| Breeding adults (spring-summer) | | |
| Ice trawler vs. double beam trawler | $\chi^2_1 = 497.7$, P < 0.001 | $\chi^2_1 = 120.8$, $P <$ 0.001 |
| Wintering adults (autumn-winter) | | |
| Ice trawler vs. double beam trawler vs. jigger | $\chi^2_2 = 978.5$, P < 0.001* | $\chi^2_1 = 5.5$, $P = 0.02$ |
| Juveniles | | |
| Ice trawler vs. double beam trawler vs. jigger | $\chi^2_2 = 243.4$, P < 0.001* | $\chi^2_2 = 41.83$, P < 0.001* |

* Results of Tukey's test (P < 0.001) described in text.

threat increases) to an alteration on sex ratios and a consequent population decline, considering that sex-biased survival in seabird populations has important implications in effective population size as creates a bottleneck, inhibiting population growth (Gownaris and Boersma, 2019). Although in population viability of long-lived low-fecundity species adult survival would be more important than juvenile mortality, conservation actions focusing on juveniles and/or chicks would contribute to slow declines (Finkelstein et al., 2010; Frankish et al., 2020). Therefore, special attention should be given to manage and regulate the debris that affects these age classes.

Our results suggest that monitoring and mitigation measures focusing on reducing debris originated by specific fleets (shrimp and squid fisheries), would contribute to reduce the plastic ingestion by chicks, breeding adults, juveniles, and wintering adults. Furthermore, measures to properly manage open sky dumpsters from coastal cities, extending simultaneously producer responsibility and promoting circular economy (Ronda et al., 2021) would contribute to reduce plastic consumption mainly by chicks and juveniles. Additionally these measures may favor several species that inhabit the Argentine continental shelf that are also known to largely interact with marine debris (Denuncio et al., 2011; Jiménez et al., 2015; González Carman et al., 2016; Denuncio et al., 2017; Alzugaray et al., 2020; Ronda et al., 2021). Finally, the fact that accumulation areas along the Argentine continental shelf were described, highlights the importance of this study in filling up gaps of information that could be applicable to marine wildlife (Vegter et al., 2014). Nonetheless, the extent and magnitude of impacts of plastics on the Southern Giant Petrel population from Patagonia remain unknown, highlighting the need for further research.

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## CRediT authorship contribution statement

G.S.B., L.G. and F.Q. conceived the study. G.S.B. and F.Q. collected data. M.H.T. developed the circulation model and experiments. G.S.B. analyzed spatial data. L.G. completed statistical analysis. G.S.B., M.H.T, L.G., and F.Q. wrote the initial manuscript. G. D-O. provided resources. All authors contributed to the reviewing and editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113767.

## References

Acha, E.M., Mianzan, H.W., Guerrero, R.A., Favero, M., Bava, J., 2004. Marine fronts at the continental shelves of austral South America: physical and ecological processes. J. Mar. Syst. 44 (1–2), 83–105.

Alzugaray, L., Di Martino, M., Beltramino, L., Rowntree, V., Sironi, M., Uhart, M., 2020. Anthropogenic debris in the digestive tract of a southern right whale (Eubalaena australis) stranded in Golfo Nuevo, Argentina. Mar. Pollut. Bull. 161, 111738.

Allega, L., Pisoni, J.P., Cozzolino, E., Maenza, R.A., Piccolo, M.C., 2021. The variability of sea surface temperature in the Patagonian shelf Argentina, from 35 years of satellite information. Int. J. Remote Sens. 42 (16), 6092–6108.

Arata, J., Croxall, J., Huin, N., Nicholls, D., Phillips, R., Quintana, F.R., et al., 2009. Albatros.

Argos-CLS, 2011. Argos User Manual Worldwide Tracking and Environmental Monitoring by Satellite. CLS Service Argos, Ramonville Saint-Anne.

Auman, H.J., Ludwig, J.P., Giesy, J.P., Colborn, T., 1997. Plastic ingestion by Laysan albatross chicks on Sand Island, Midway Atoll, in 1994 and 1995. In: Albatross Biology and Conservation 239244.

Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc., B 364 (1526), 1985–1998.

Barnes, D.K., Morley, S.A., Bell, J., Brewin, P., Brigden, K., Collins, M., et al., 2018. Marine plastics threaten giant Atlantic marine protected areas. Curr. Biol. 28 (19), R1137–R1138.

BirdLife International, 2018. Macronectes giganteus. In: The IUCN Red List of Threatened Species 2018. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22697852A132608499.en e.T22697852A132608499.

Blanco, G.S., Pisoni, J.P., Quintana, F., 2015. Characterization of the seascape used by juvenile and wintering adult southern Giant petrels from Patagonia Argentina. Estuar. Coast. Shelf Sci. 153, 135–144.

Blanco, G.S., Quintana, F., 2014. Differential use of the argentine shelf by wintering adults and juveniles southern giant petrels, Macronectes giganteus, from Patagonia. Estuar. Coast. Shelf Sci. 149, 151–159.

Blanco, G.S., Sánchez-Carnero, N., Pisoni, J.P., Quintana, F., 2017. Seascape modeling of southern giant petrels from Patagonia during different life-cycles. Mar. Biol. 164 (3), 1–14.

Calenge, C., 2006. The package "adehabitat" for the R software: a tool for the analysis of space and habitat use by animals. Ecol. Model. 197 (3–4), 516–519.

Carey, M.J., 2011. Intergenerational transfer of plastic debris by short-tailed shearwaters (Ardenna tenuirostris). Emu 111 (3), 229–234.

Combes, V., Matano, R.P., 2014. A two-way nested simulation of the oceanic circulation in the southwestern Atlantic. J. Geophys. Res.: Oceans 119 (2), 731–756.

Combes, V., Matano, R.P., 2018. The Patagonian shelf circulation: drivers and variability. Prog. Oceanogr. 167, 24–43.

Combes, V., Matano, R.P., 2019. On the origins of the low-frequency sea surface height variability of the Patagonia shelf region. Ocean Model. 142, 101454.

Congdon, B.C., Krockenberger, A.K., Smithers, B.V., 2005. Dual-foraging and co-ordinated provisioning in a tropical procellariiform, the wedge-tailed shearwater. Mar. Ecol. Prog. Ser. 301, 293–301.

Connan, M., Mayzaud, P., Boutoute, M., Weimerskirch, H., Cherel, Y., 2005. Lipid composition of stomach oil in a procellariiform seabird Puffinus tenuirostris: implications for food web studies. Mar. Ecol. Prog. Ser. 290, 277–290.

Copello, S., Dogliotti, A.I., Gagliardini, D.A., Quintana, F., 2011. Oceanographic and biological landscapes used by the southern Giant petrel during the breeding season at the Patagonian shelf. Mar. Biol. 158 (6), 1247–1257.

Copello, S., Quintana, F., 2009a. Breeding biology of the southern giant petrel (Macronectes giganteus) in Patagonia, Argentina. Rev. Ornitol. Neotrop. 20, 369–380.

Copello, S., Quintana, F., 2009b. Spatio-temporal overlap between the at-sea distribution of southern Giant petrels and fisheries at the Patagonian shelf. Polar Biol. 32 (8), 1211–1220.

Copello, S., Quintana, F., Pérez, F., 2008. Diet of the southern giant petrel in Patagonia: fishery-related items and natural prey. Endanger. Species Res. 6 (1), 15–23.

Copello, S., Quintana, F., Somoza, G., 2006. Sex determination and sexual size-dimorphism in Southern Giant-Petrels (Macronectes giganteus) from Patagonia, Argentina. EMU-Austral Ornithol. 106 (2), 141–146.

Copello, S., Quintana, F.R., 2003. Marine Debris Ingestion by Southern Giant Petrels and Its Potential Relationships With Fisheries in the Southern Atlantic Ocean.

Crawley, M., 2007. The R Book. John Wiley & Sons, Chichester, UK.

Croxall, J., Prince, P., 1980. Food, feeding ecology and ecological segregation of seabirds at South Georgia. Biol. J. Linn. Soc. 14 (1), 103–131.

Croxall, J., Wood, A., 2002. The importance of the Patagonian shelf for top predator species breeding at South Georgia. Aquat. Conserv. Mar. Freshwat. Ecosyst. 12 (1), 101–118.

Dato, C., Bambill, G., Cañete, G., Villarino, M., Aubone, A., 2006. Estimación cuantitativa del descarte en la pesquería de merluza realizado por la flota comercial argentina. In: INIDEP Documento Científico 6. Secretaría de Agricultura, Ganadería, Pesca y Alimentos, Mar del Plata, Argentina.

Debreu, L., Marchesiello, P., Penven, P., Cambon, G., 2012. Two-way nesting in split-explicit ocean models: algorithms, implementation and validation. Ocean Model. 49, 1–21.

Denuncio, P., Bastida, R., Dassis, M., Giardino, G., Gerpe, M., Rodríguez, D., 2011. Plastic ingestion in Franciscana dolphins, Pontoporia blainvillei (Gervais and d'Orbigny, 1844), from Argentina. Mar. Pollut. Bull. 62 (8), 1836–1841.

Denuncio, P., Mandiola, M.A., Salles, S.B.P., Machado, R., Ott, P.H., De Oliveira, L.R., et al., 2017. Marine debris ingestion by the South American fur seal from the Southwest Atlantic Ocean. Mar. Pollut. Bull. 122 (1–2), 420–425.

Dias, M.P., Martin, R., Pearmain, E.J., Burfield, I.J., Small, C., Phillips, R.A., et al., 2019. Threats to seabirds: a global assessment. Biol. Conserv. 237, 525–537.

Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., et al., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9 (12), e111913.

Favero, M., Blanco, G., García, G., Copello, S., Seco Pon, J., Frere, E., et al., 2011. Seabird mortality associated with ice trawlers in the Patagonian shelf: effect of discards on the occurrence of interactions with fishing gear. Anim. Conserv. 14 (2), 131–139.

Favero, M., Khatchikian, C.E., Arias, A., Rodriguez, M.P.S., Cañete, G., Mariano-Jelicich, R., 2003. Estimates of seabird by-catch along the Patagonian shelf by Argentine longline fishing vessels, 1999–2001. Bird Conserv. Int. 13 (4), 273–281.

Favero, M., Silva Rodríguez, M.P., 2005. Estado actual y conservación de aves pelágicas que utilizan la plataforma continental Argentina Como área de alimentación. Hornero 20 (1), 95–110.

Finkelstein, M., Doak, D., Nakagawa, M., Sievert, P., Klavitter, J., 2010. Assessment of demographic risk factors and management priorities: impacts on juveniles substantially affect population viability of a long-lived seabird. Anim. Conserv. 13 (2), 148–156.

Franco, B.C., Palma, E.D., Combes, V., Acha, E.M., Saraceno, M., 2018. Modeling the offshore export of subantarctic shelf waters from the Patagonian shelf. J. Geophys. Res. Oceans 123 (7), 4491–4502.

Frankish, C.K., Phillips, R.A., Clay, T.A., Somveille, M., Manica, A., 2020. Environmental drivers of movement in a threatened seabird: insights from a mechanistic model and implications for conservation. Divers. Distrib. 26 (10), 1315–1329.

Góngora, M.E., González-Zevallos, D., Pettovello, A., Mendía, L., 2012. Caracterización de las principales pesquerías del golfo San Jorge Patagonia, Argentina. Latin Am. J. Aquat. Res. 40 (1), 1–11.

González-Zevallos, D., Yorio, P., 2006. Seabird use of discards and incidental captures at the Argentine hake trawl fishery in the Golfo San Jorge, Argentina. Mar. Ecol. Prog. Ser. 316, 175–183.

González Carman, V., Mandiola, A., Alemany, D., Dassis, M., Seco Pon, J.P., Prosdocimi, L., et al., 2016. Distribution of megafaunal species in the southwestern Atlantic: key ecological areas and opportunities for marine conservation. ICES J. Mar. Sci. 73 (6), 1579–1588.

Gownaris, N.J., Boersma, P., 2019. Sex-biased survival contributes to population decline in a long-lived seabird, the magellanic penguin. Ecol. Appl. 29 (1), e01826.

Guihou, K., Piola, A.R., Palma, E.D., Chidichimo, M.P., 2020. Dynamical connections between large marine ecosystems of austral South America based on numerical simulations. Ocean Sci. 16 (2), 271–290.

Hammer, J., Kraak, M.H., Parsons, J.R., 2012. Plastics in the marine environment: the dark side of a modern gift. Rev. Environ. Contam. Toxicol. 1–44.

Hunter, S., 1985. The role of giant petrels in the Southern Ocean ecosystem. In: Antarctic Nutrient Cycles and Food Webs. Springer, pp. 534–542.

Hyrenbach, K.D., Hester, M.M., Adams, J., Titmus, A.J., Michael, P., Wahl, T., et al., 2017. Plastic ingestion by black-footed albatross Phoebastria nigripes from Kure atoll, Hawai'i: linking chick diet remains and parental at-sea foraging distributions. Mar. Ornithol. 45, 225–236.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Jenouvrier, S., Barbraud, C., Weimerskirch, H., 2005. Long-term contrasted responses to climate of two Antarctic seabird species. Ecology 86 (11), 2889–2903.

Jiménez, S., Domingo, A., Brazeiro, A., Defeo, O., Phillips, R.A., 2015. Marine debris ingestion by albatrosses in the Southwest Atlantic Ocean. Mar. Pollut. Bull. 96 (1–2), 149–154.

Krüger, L., Paiva, V.H., Petry, M.V., Ramos, J.A., 2017. Strange lights in the night: using abnormal peaks of light in geolocator data to infer interaction of seabirds with nocturnal fishing vessels. Polar Biol. 40 (1), 221–226.

Lambert, S., Sinclair, C., Boxall, A., 2014. Occurrence, degradation, and effect of polymer-based materials in the environment. Rev. Environ. Contam. Toxicol. 227, 1–53.

Lavers, J.L., Bond, A.L., Hutton, I., 2014. Plastic ingestion by flesh-footed shearwaters (Puffinus carneipes): implications for fledgling body condition and the accumulation of plastic-derived chemicals. Environ. Pollut. 187, 124–129.

Lavers, J.L., Hutton, I., Bond, A.L., 2019. Clinical pathology of plastic ingestion in marine birds and relationships with blood chemistry. Environ. Sci. Technol. 53 (15), 9224–9231.

Lebreton, L.-M., Greer, S., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64 (3), 653–661.

Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci. Rep. 9 (1), 1–10.

Lindström, J., 1999. Early development and fitness in birds and mammals. Trends Ecol. Evol. 14 (9), 343–348.

Mallory, M.L., Gilbert, C.D., 2008. Leg-loop harness design for attaching external transmitters to seabirds. Mar. Ornithol. 36, 183–188.

Marinao, C., Góngora, M.E., González-Zevallos, D., Yorio, P., 2014. Factors affecting magellanic penguin mortality at coastal trawlers in Patagonia, Argentina. Ocean Coast. Manag. 93, 100–105.

Matano, R., Palma, E.D., Piola, A.R., 2010. The influence of the Brazil and Malvinas currents on the southwestern Atlantic shelf circulation. Ocean Sci. 6 (4), 983–995.

Matano, R.P., Combes, V., Piola, A.R., Guerrero, R., Palma, E.D., Ted Strub, P., et al., 2014. The salinity signature of the cross-shelf exchanges in the southwestern Atlantic Ocean: numerical simulations. J. Geophys. Res. Oceans 119 (11), 7949–7968.

Morrison, K.W., Hipfner, J.M., Gjerdrum, C., Green, D.J., 2009. Wing length and mass at fledging predict local juvenile survival and age at first return in tufted puffins. Condor 111 (3), 433–441.

North, E., Hood, R., Chao, S.-Y., Sanford, L., 2006. Using a random displacement model to simulate turbulent particle motion in a baroclinic frontal zone: a new implementation scheme and model performance tests. J. Mar. Syst. 60 (3–4), 365–380.

Palma, E.D., Matano, R.P., Piola, A.R., 2004. A numerical study of the southwestern Atlantic shelf circulation: barotropic response to tidal and wind forcing. J. Geophys. Res.: Oceans 109 (C8).

Palma, E.D., Matano, R.P., Piola, A.R., 2008. A numerical study of the southwestern Atlantic shelf circulation: stratified ocean response to local and offshore forcing. J. Geophys. Res.: Oceans 113 (C11).

Palma, E.D., Matano, R.P., Tonini, M.H., Martos, P., Combes, V., 2020. Dynamical analysis of the oceanic circulation in the Gulf of San Jorge, Argentina. J. Mar. Syst. 203, 103261.

Petry, M.V., da Silva Fonseca, V.S., Scherer, A.L., 2007. Analysis of stomach contents from the black-browed albatross, Thalassarche melanophris, on the Coast of Rio Grande do Sul, Southern Brazil. Polar Biol. 30 (3), 321–325.

Phillips, R.A., Gales, R., Baker, G., Double, M., Favero, M., Quintana, F., et al., 2016. The conservation status and priorities for albatrosses and large petrels. Biol. Conserv. 201, 169–183.

Phillips, R.A., Waluda, C.M., 2020. Albatrosses and petrels at South Georgia as sentinels of marine debris input from vessels in the Southwest Atlantic Ocean. Environ. Int. 136, 105443.

Pierce, K.E., Harris, R.J., Larned, L.S., Pokras, M.A., 2004. Obstruction and starvation associated with plastic ingestion in a Northern Gannet Morus bassanus and a greater shearwater Puffinus gravis. Mar. Ornithol. 32, 187–189.

Prokić, M.D., Radovanović, T.B., Gavrić, J.P., Faggio, C., 2019. Ecotoxicological effects of microplastics: examination of biomarkers, current state and future perspectives. TrAC Trends Anal. Chem. 111, 37–46.

Puskic, P.S., Lavers, J.L., Bond, A.L., 2020. A critical review of harm associated with plastic ingestion on vertebrates. Sci. Total Environ. 140666.

Quintana, F., Dell'Arciprete, O.P., Copello, S., 2010. Foraging behavior and habitat use by the southern Giant petrel on the Patagonian shelf. Mar. Biol. 157 (3), 515–525.

Quintana, F., Punta, G., Copello, S., Yorio, P., 2006. Population status and trends of southern giant petrels (Macronectes giganteus) breeding in North Patagonia, Argentina. Polar Biol. 30 (1), 53–59.

Quintana, F.R., Croxall, J., González Solís, J., Phillips, R., Trathan, P., Falabella, V., 2009. Petreles.

R Development Core Team, 2019. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.r-project.org.

Rodríguez, A., Rodríguez, B., Carrasco, M.N., 2012. High prevalence of parental delivery of plastic debris in Cory's shearwaters (Calonectris diomedea). Mar. Pollut. Bull. 64 (10), 2219–2223.

Roman, L., Bell, E., Wilcox, C., Hardesty, B.D., Hindell, M., 2019. Ecological drivers of marine debris ingestion in Procellariiform Seabirds. Sci. Reports 9 (1), 1–8.

Ronda, A.C., Arias, A.H., Rimondino, G.N., Pérez, A.F., Harte, A., Marcovecchio, J.E., 2021. Plastic impacts in Argentina: a critical research review contributing to the global knowledge. Curr. Environ. Health Rep. 8 (3), 212–222.

Ryan, P.G., 2015. How quickly do albatrosses and petrels digest plastic particles? Environ. Pollut. 207, 438–440.

Santos, H.M., 2010. In: Pesquero, C.F. (Ed.), Plan de acción nacional para reducir la interacción de aves con pesquerías en la República Argentina.

Senko, J.F., Nelms, S.E., Reavis, J.L., Witherington, B., Godley, B.J., Wallace, B.P., 2020. Understanding individual and population-level effects of plastic pollution on marine megafauna. Endanger. Species Res. 43, 234–252.

Sheavly, S., Register, K., 2007. Marine debris & plastics: environmental concerns, sources, impacts and solutions. J. Polym. Environ. 15 (4), 301–305.

Strub, P.T., James, C., Combes, V., Matano, R.P., Piola, A.R., Palma, E.D., et al., 2015. Altimeter-derived seasonal circulation on the southwest a tlantic shelf: 27°–43° S. J. Geophys. Res. Oceans 120 (5), 3391–3418.

Suaria, G., Perold, V., Lee, J.R., Lebouard, F., Aliani, S., Ryan, P.G., 2020. Floating macro-and microplastics around the Southern Ocean: results from the Antarctic circumnavigation expedition. Environ. Int. 136, 105494.

Techow, N., O'Ryan, C., Phillips, R., Gales, R., Marin, M., Patterson-Fraser, D., et al., 2010. Speciation and phylogeography of giant petrels macronectes. Mol. Phylogenet. Evol. 54 (2), 472–487.

Titmus, A.J., Hyrenbach, K.D., 2011. Habitat associations of floating debris and marine birds in the north East Pacific Ocean at coarse and meso spatial scales. Mar. Pollut. Bull. 62 (11), 2496–2506.

Tonini, M.H., Palma, E.D., Piola, A.R., 2013. A numerical study of gyres, thermal fronts and seasonal circulation in austral semi-enclosed gulfs. Cont. Shelf Res. 65, 97–110.

UNEP, 2021. From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution United Nations Environment Programme.

Van Franeker, J.A., Law, K.L., 2015. Seabirds, gyres and global trends in plastic pollution. Environ. Pollut. 203, 89–96.

Vegter, A.C., Barletta, M., Beck, C., Borrero, J., Burton, H., Campbell, M.L., et al., 2014. Global research priorities to mitigate plastic pollution impacts on marine wildlife. Endanger. Species Res. 25 (3), 225–247.

Weimerskirch, H., 1998. How can a pelagic seabird provision its chick when relying on a distant food resource? Cyclic attendance at the colony, foraging decision and body condition in sooty shearwaters. J. Anim. Ecol. 67 (1), 99–109.

Weimerskirch, H., Collet, J., Corbeau, A., Pajot, A., Hoarau, F., Marteau, C., et al., 2020. Ocean sentinel albatrosses locate illegal vessels and provide the first estimate of the extent of nondeclared fishing. Proc. Natl. Acad. Sci. 117 (6), 3006–3014.

Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. 112 (38), 11899–11904.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed effects modelling for nested data. In: Mixed Effects Models and Extensions in Ecology With R. Springer, pp. 101–142.