



Tracking juveniles confirms fisheries-bycatch hotspot for an endangered albatross

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ARTICLE INFO

Keywords:

Albatross
Biologging
Bycatch mitigation
Longline fisheries
Marine megafauna
Ontogeny
Seabird bycatch

ABSTRACT

Fisheries bycatch is a major threat to marine megafauna such as seabirds. Population monitoring has revealed low survival of juvenile seabirds over recent decades, potentially because naïve individuals are more susceptible to bycatch than adults. However, major gaps remain in our knowledge of behavior and interaction of juveniles with fisheries. Here, we tracked juvenile grey-headed albatrosses (*Thalassarche chrysostoma*) from South Georgia - the largest global population of this endangered species, and in rapid decline - to investigate their at-sea distribution and assess bycatch risk. Fledged juveniles dispersed to the northeast, overlapping with a bycatch hotspot for grey-headed albatrosses reported by the Japanese pelagic longline fleet in the southeast Atlantic Ocean. Given adult grey-headed albatrosses use regions less exposed to fishing activity (< 40°S), the majority of birds bycaught in this area are probably juveniles, and possibly immatures, from South Georgia, likely representing a key factor explaining the sustained population decline. Our study highlights the urgent need to uncover the 'lost-years' for marine megafauna to enable focused conservation efforts.

1. Introduction

Incidental mortality (bycatch) of seabirds in fisheries is a major conservation problem affecting numerous species worldwide, in particular albatrosses and large petrels (Phillips et al., 2016). These long-lived birds have extensive ranges which bring them into potential conflict with diverse fleets across the globe, and even small reductions in their survival have dramatic impacts on population dynamics (Arnold et al., 2006; Clay et al., 2019; Carneiro et al., 2020). Initial evidence of this threat came from recoveries of ringed birds in longline fisheries in the 1980s (Croxall and Prince, 1990). Electronic tracking has since become an essential tool for identifying potential bycatch hotspots, as tracks can be overlaid on the distribution of fishing effort, helping to focus conservation efforts in time and space (Croxall and Nicol, 2004; Suryan et al., 2007; Copello et al., 2014).

The year-round distribution and bycatch risk of adults is known for many species of albatrosses and large petrels; however, major gaps

remain in our knowledge of distributions of juveniles and immatures (Carneiro et al., 2020). These younger life-history stages are challenging to track because of the long periods spent at sea between independence and first return to breeding colonies, termed the 'lost years' (Hazen et al., 2012). However, existing studies suggest that juveniles disperse more widely than migrating adults, potentially increasing exposure to bycatch risk (Weimerskirch et al., 2006; Trebilco et al., 2008; Frankish et al., 2020). As juveniles and immatures account for >50% of the population in seabirds, high juvenile mortality can hamper the recovery of threatened species, and even cause population decline if chronic mortality substantially reduces recruitment (Weimerskirch et al., 1997; Pardo et al., 2017; Carneiro et al., 2020). Understanding age-related differences in movement patterns is therefore a priority for informing effective bycatch-mitigation strategies.

The grey-headed albatross (*Thalassarche chrysostoma*) was uplisted from Vulnerable to Endangered in 2018 by the IUCN (IUCN, 2019), largely due to the continued steep decline of by far the largest global

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population, which breeds at South Georgia (Poncet et al., 2017). Their circumpolar distribution and propensity to forage at oceanic frontal zones brings them into potential conflict with fisheries, particularly pelagic longlines targeting tuna and billfishes (Scombridae) within multiple Regional Fisheries Management Organizations (RFMOs; Croxall et al., 2005; Clay et al., 2016, 2019). However, a recent assessment of bycatch risk of adult birds concluded that spatial overlap with fishing effort was lower than in other sympatric albatrosses, and likely insufficient to account for the steep population decline (Clay et al., 2019). Nonetheless, over the last few decades (between 1997 and 2015) observers on Japanese vessels have reported high bycatch of grey-headed albatrosses in the central southeast Atlantic Ocean (35–45°S, 10°W–20°E) (Inoue et al., 2012; Katsumata et al., 2017). The provenance of these birds has been a puzzle, as the region is rarely used by adults from either South Georgia or Indian Ocean colonies (Clay et al., 2016), thereby indicating that other life-history stages (such as juveniles) may be particularly susceptible.

Here, we examine overlap between pelagic longline fisheries operating in the South Atlantic, Indian and Pacific Oceans and grey-headed albatrosses from South Georgia, incorporating new tracking data collected in 2018 and 2019 from juveniles. We aimed to fill key gaps in knowledge of at-sea distribution of juveniles and compare their potential bycatch risk with adults, describing monthly variation in movement patterns and fisheries overlap, and identifying periods, regions and fleets of greatest concern.

2. Methods

2.1. At-sea distribution of juveniles and adults

2.1.1. Tracking data processing

Tracking data were obtained from adult and post-fledgling juveniles from Bird Island, South Georgia (54°00'S, 38°03'W). Duty-cycled Platform Terminal Transmitters (PTTs) were deployed on grey-headed albatross (GHA) chicks prior to fledging in May–June 2006, 2018 and 2019. Seven PTTs were deployed in 2006 (for details see Clay et al., 2019), and 16 PTTs (Telonics TA-2630) in both 2018 and 2019. Seven and two chicks in 2018 and 2019, respectively, died before leaving the island, or shortly thereafter (probably depredated by giant petrel *Macronectes* spp.), as transmissions at sea ceased within 1 day. Between 24 and 940 locations were obtained from each of the remaining PTTs ($n = 28$), covering a period between May and December (see Table 1 for complete metadata). Tracking data for breeding and non-breeding adults were collected between 1993 and 2012 using PTTs, GPS (Global Positioning System) loggers and geolocators (Global Location Sensors or GLS) (for deployment details, see for e. g. Phillips et al., 2004b; Clay et al., 2016). In all cases, the total mass of devices including attachments were less than the 3% threshold of body mass beyond which deleterious effects are more common in pelagic seabirds (Phillips et al., 2003).

All locations from PTTs in ARGOS classes A, B, 0, 1 and 3 were used, but unrealistic positions requiring a sustained flight speed of over 90 km·h⁻¹ were removed (McConnell et al. 1992). Light data from geolocators were processed using MultiTrace Geolocation or BASTrak

software, providing two positions per day with a mean error of 186 ± 114 km (Phillips et al., 2004a). Locations with interruptions around sunrise and sunset, and periods for 3–4 weeks around the equinoxes when latitude cannot be estimated reliably, were excluded. PTT and GPS data were interpolated at hourly intervals to obtain regular positions. GLS data were not interpolated as locations are available at regular, approximately 12-hour, intervals. In total, 329 tracks from 156 adults were used in analyses (Incubation: 25 tracks from 25 individuals; Brood: 86 tracks from 63 individuals, Post-Brood: 158 tracks from 20 individuals and Non-breeding: 55 tracks from 55 individuals).

A resampling procedure was carried out to determine whether sample sizes for juveniles were sufficient to represent population-level space use, as in Clay et al. (2019). This was not the case, and therefore although we tracked 28 juveniles, the subsequent analysis represents the at-sea distribution of the sampled individuals and may underestimate the actual population distribution (Appendix 1). We therefore conducted a sensitivity analysis to assess the effect of sample size on relative overlap with pelagic longline fisheries (described below in Section 2.2.2). As for adults, a previous gap analysis indicated that sample sizes were adequate to represent home ranges during all breeding and nonbreeding periods (Clay et al., 2019).

2.1.2. Generating juvenile and adult at-sea distributions

Monthly distribution grids for juveniles and adults were generated using kernel analysis in the *adehabitatHR* package (Calenge 2006). A fixed smoothing parameter (h) of 50 km or 200 km was used for PTT and GPS data, and for GLS data, respectively, and a grid cell size of 10 km was used for all device types to enable averaging across grids. Interpolated hourly PTT and GPS data from the same breeding stage were pooled before kernel analysis. If PTT and geolocator data were available for the same breeding stage, distribution grids were weighted according to sample size before merging the two datasets. Grids were generated for all months if sample sizes for each life-history stage were ≥ five individuals (May–September). A rectangle corresponding to the bycatch hotspot reported in the southeast Atlantic Ocean (International Commission for the Conservation of the Atlantic Tunas [ICCAT] subareas 6, 7 and 8 during quarters 2 [April–June] and 3 [July–September]; Inoue et al., 2012; Katsumata et al., 2017) was overlaid on these grids and maps of spatial overlap with fishing effort (see below).

2.2. Analysis of spatial overlap between GHA and fisheries

2.2.1. Fishing effort data

Effort data for pelagic longline fisheries (number of hooks deployed, by 5 × 5° square) were collated for all tuna RFMO from publically-available databases: Indian Ocean Tuna Commission (IOTC), ICCAT, Western and Central Pacific Fisheries Commission (WCPFC), Inter-American Tropical Tuna Commission (IATTC). Effort data from the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) were not considered as these data are also reported to the other four RFMOs (Clay et al., 2019). Monthly effort data were available for all RFMOs except WCPFC, for which quarterly effort data was converted into monthly estimates by dividing effort equally. Although effort may not have been consistent over time, this assumption is unlikely to have

Table 1

Deployment metadata for juvenile grey-headed albatrosses tracked from Bird Island, South Georgia, in 2006, 2018 and 2019 using Platform Terminal Transmitters (PTTs).

Year	Device type	Duty-cycling regime	No. PTTs deployed	Tracks retained post-processing	No. locations per track	Mean ± SD track duration in days	Tracking period
2006	Microwave PTT-100	24 h on, 48 h off	7	5	24–53	17.2 ± 6.0	5 May–6 June
2018	Telonics TAV-2630	8 h on, 48 h off	16	9	260–940	101.1 ± 47.5	24 May–12 December
2019	Telonics TAV-2630	8 h on, 48 off	16	14	53–849	82.7 ± 54.3	12 May–27 October

affected results as WCPFC contributed little to overlap scores (see Tables S2 and S3). Where the areas of competence of RFMOs overlapped in space (i.e. double-reporting), duplicate values were filtered by choosing the maximum number of hooks reported by a given fleet to the RFMOs for a given $5 \times 5^\circ$ grid square. Analyses were of the monthly mean effort for the period 2010–2018.

2.2.2. Risk analysis

Monthly spatial overlap between tracked juveniles and adults, and pelagic longline fishing effort was calculated by multiplying the number of hooks by the proportion of the distribution of each life-history stage in each $5 \times 5^\circ$ square, by month (similarly to Clay et al., 2019; Carneiro et al., 2020). We used a jackknife procedure (i.e., withholding one individual bird in turn) to determine the sensitivity of the monthly overlap scores to the sample of tracked birds.

All data manipulations and analyses were conducted in R ver. 3.6.2. (R Core Team, 2020).

3. Results

3.1. At-sea distribution of juvenile and adult GHA

Juvenile grey-headed albatrosses were tracked for 11–194 days after fledging in May–June from Bird Island (Fig. 1), with the last transmissions received by the ARGOS system in July, December and October in 2006, 2018 and 2019, respectively (see Table 1 for full metadata).

Initially, juveniles dispersed in a northeast direction from South Georgia, then moved towards the southeast Atlantic, overlapping with ICCAT subareas 6, 7 and 8 (predominantly in May–June, although overlap of a number of birds persisted until September; Fig. 2a). Thereafter, one juvenile moved northwards towards the Namibian and Angolan coastlines (July; Figs. 1 & 2a), and the remainder continued progressively eastwards to the southwest Indian Ocean (July; Figs. 2a & S2). Three individuals dispersed even further east, reaching the southeast Indian Ocean (August; Figs. 2a & S2), New Zealand (September; Fig. 2a), and southern Chile (October onwards - one individual only; Fig. 1), and one individual returned westwards towards South Georgia (Figs. 2a & S2). PTT transmissions ceased at different points in time, so it remains unclear whether more juveniles would have dispersed as far (Table 1). Adult grey-headed albatrosses also made considerable use of the southwest Indian Ocean in the nonbreeding season (June–September; Fig. 2b). However, in contrast to juveniles, adults were more broadly distributed during May–September (Fig. 2b), using the southwest Atlantic (May–September; Fig. 2b), southeast Pacific (May; Fig. 2b) and southwest Pacific (September, Fig. 2b) Oceans. When in the southeast Atlantic Ocean, adults remained largely south of 40°S and west of 10°W , and therefore unlike juveniles, only a tiny proportion of their distribution ($<0.005\%$ vs. $[0.05\text{--}0.1\%]$ per month for adults and juveniles respectively) overlapped with ICCAT subareas 6, 7 and 8 in May–June (Fig. 2a & b).

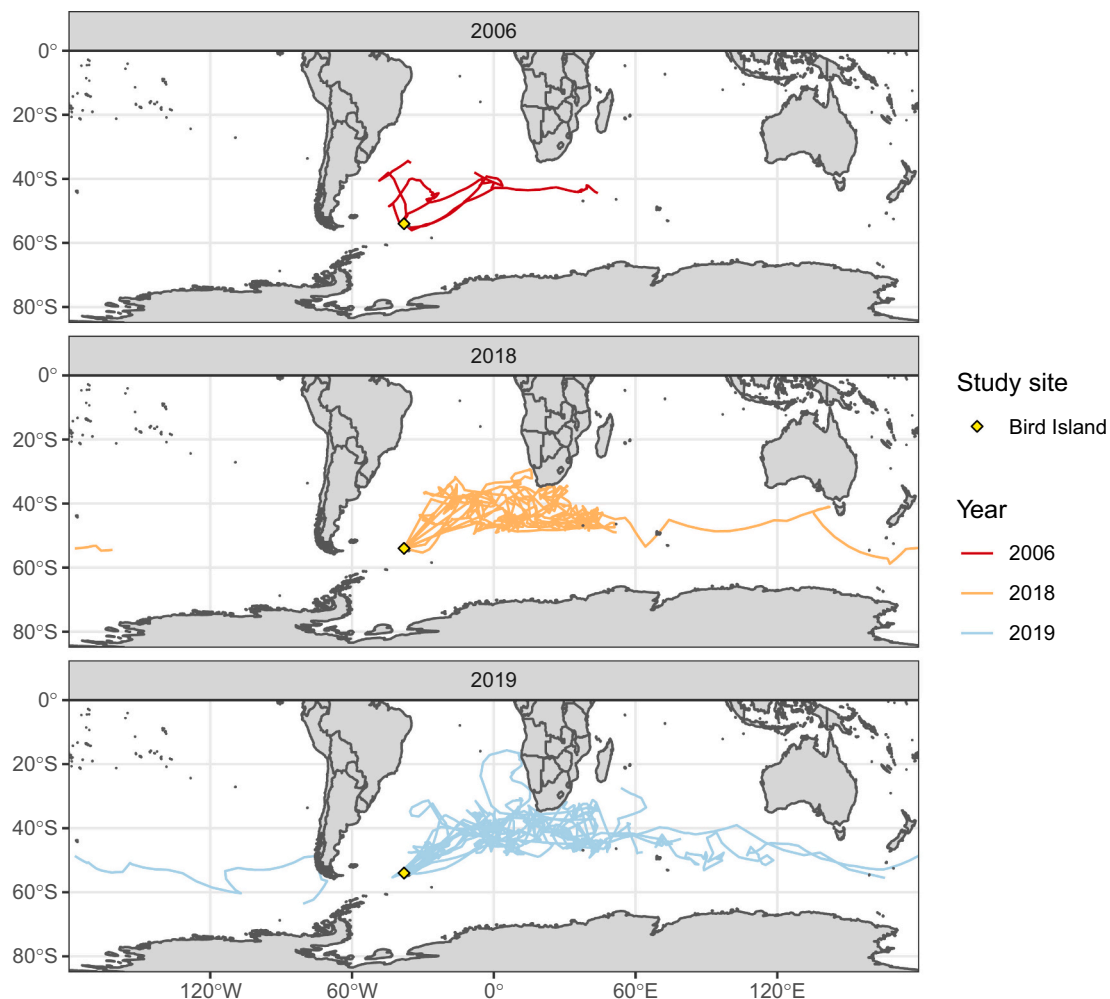


Fig. 1. At-sea distribution of juvenile grey-headed albatrosses tracked from Bird Island, South Georgia, in 2006 (May–June; $n = 5$), 2018 (May–December; $n = 9$) and 2019 (May–October; $n = 14$).

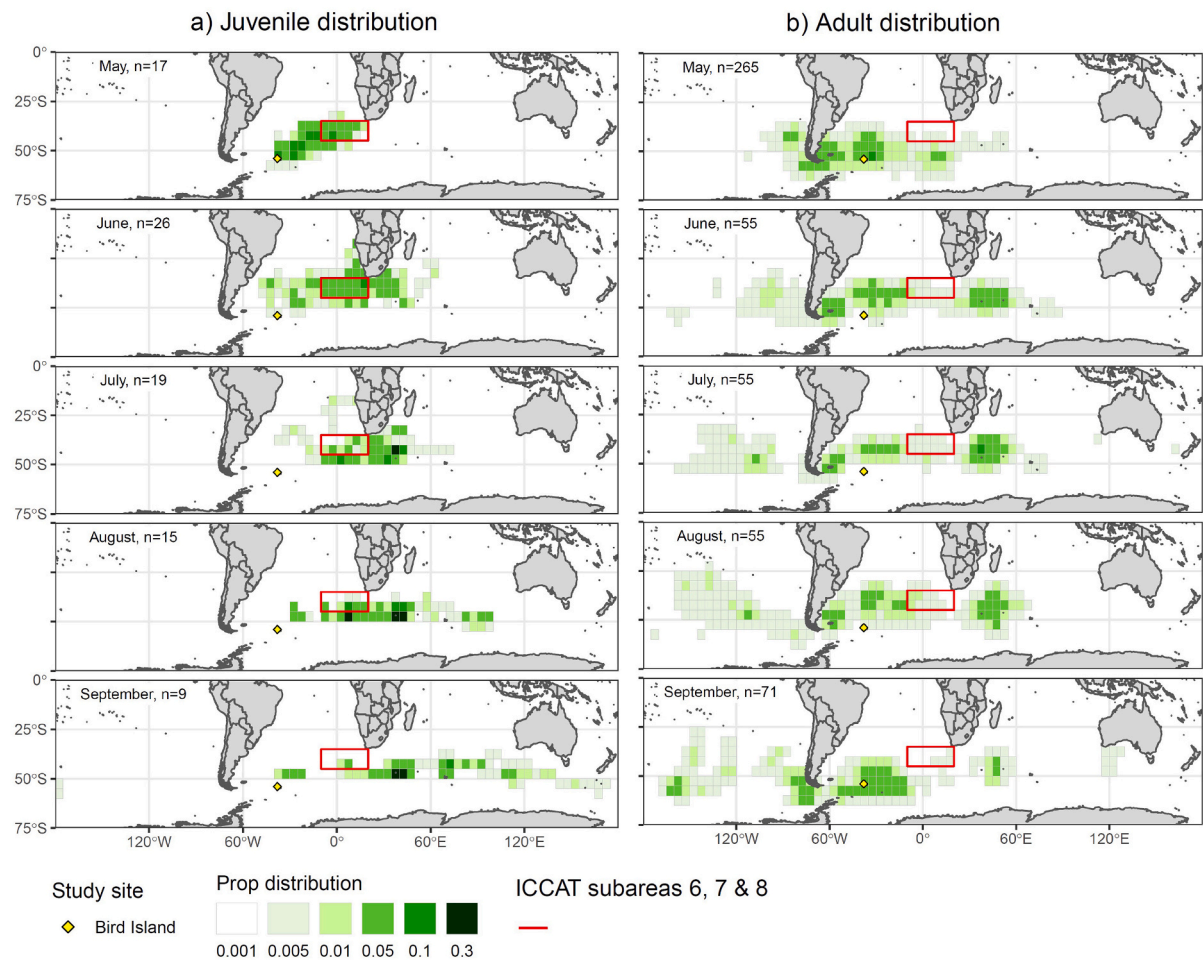


Fig. 2. Monthly (May–September) distribution in $5 \times 5^\circ$ cells of a) juvenile and b) adult grey-headed albatrosses tracked from Bird Island, South Georgia. ‘Prop distribution’ represents the proportion of the monthly distribution occurring in each $5 \times 5^\circ$ square. A bycatch hotspot for grey-headed albatrosses was reported in ICCAT subareas 6, 7 and 8 for April–June 1997–2015 (Inoue et al., 2012; Katsumata et al., 2017), and for July–September 1997–2009 (Inoue et al., 2012).

3.2. Fisheries bycatch overlap risk of juvenile and adult GHA

Average annual pelagic fishing effort in 2010–2018 was high in various regions intensively used by juveniles and adults; in particular within ICCAT subareas 6, 7 and 8 ($5 \times 5^\circ$ grid cells with up to 2 million hooks deployed annually; Fig. 3a) as well as the southwest Indian Ocean

($5 \times 5^\circ$ grid cells with up to 20 million hooks annually; Fig. 3a). As a result, overlap scores, and hence bycatch risk, were correspondingly high in the former region for juveniles, and the latter region for both life-history stages (Fig. 4a & b). Overlap with pelagic longline effort was highest for juveniles in May–July ($85\text{--}143$ [jackknife range: $66\text{--}149$] $\times 10^3$ hooks; Fig. 5a) in accordance with annual peaks in monthly pelagic

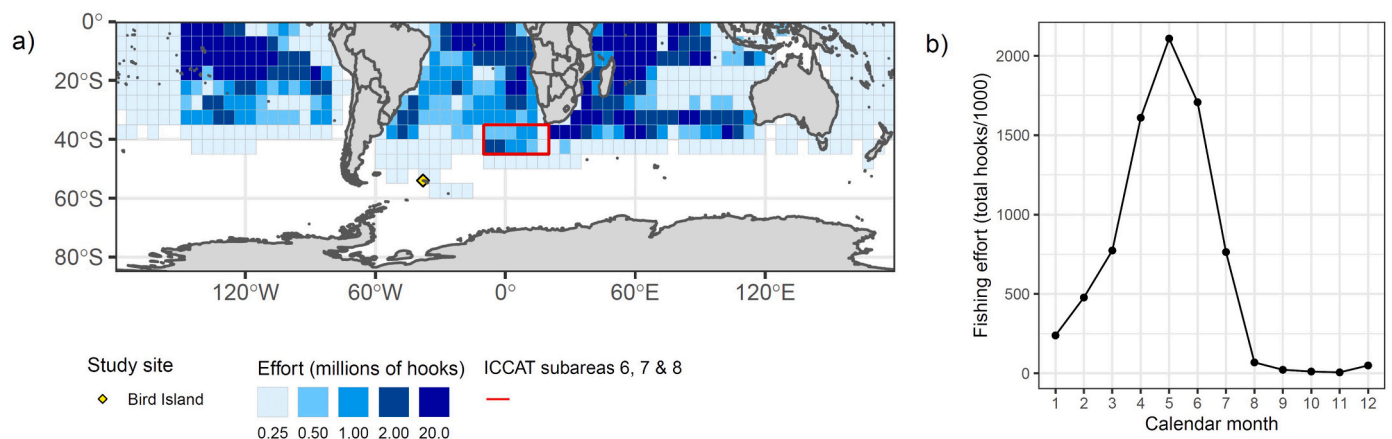


Fig. 3. a) Mean annual distribution of pelagic longline effort over the period 2010–2018. A bycatch hotspot for grey-headed albatrosses was reported in ICCAT subareas 6, 7 and 8 for April–June 1997–2015 (Inoue et al., 2012; Katsumata et al., 2017), and for July–September 1997–2009 (Inoue et al., 2012) b) Mean monthly variation in pelagic longline effort over the period 2010–2018 for ICCAT subareas 6, 7 and 8.

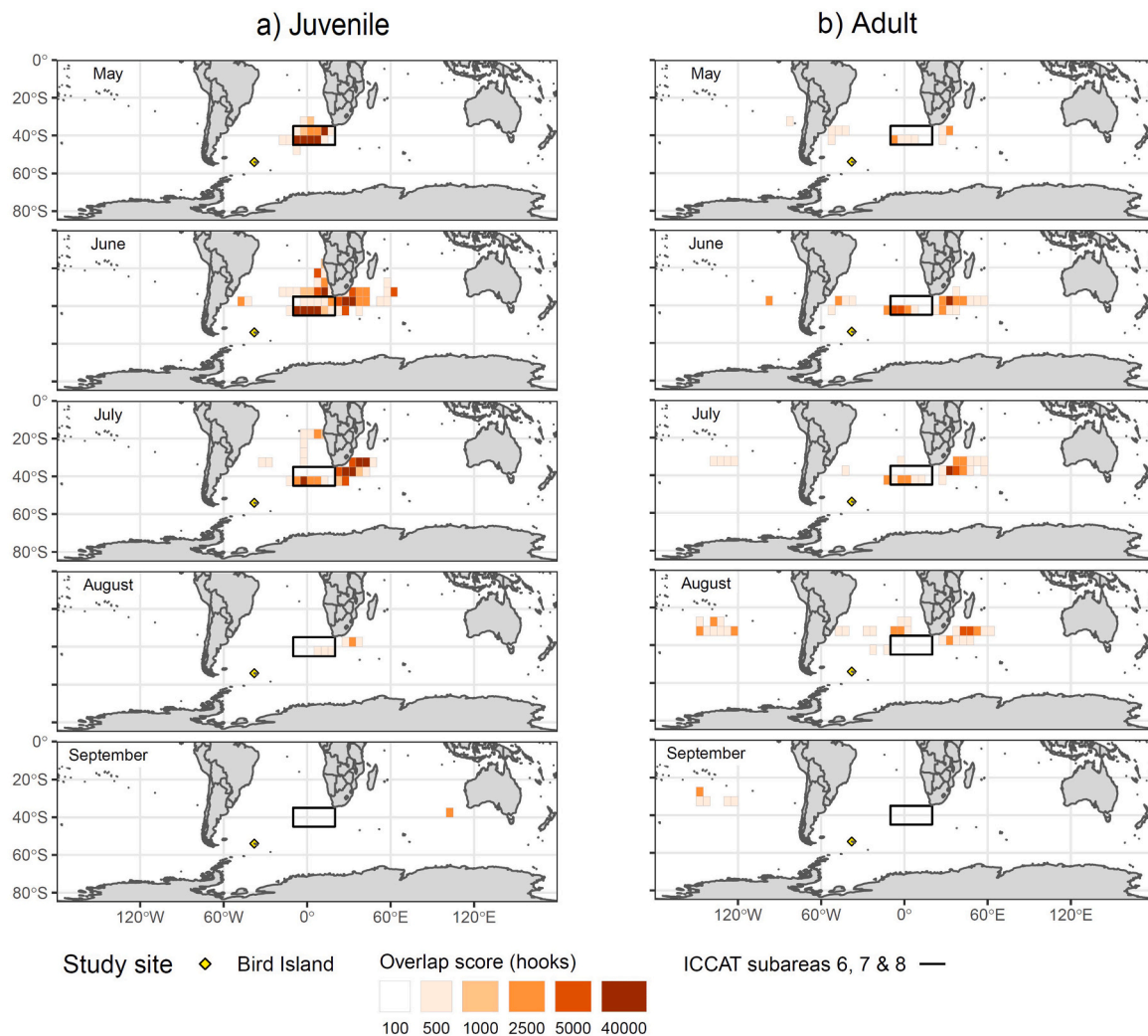


Fig. 4. Monthly overlap score of a) juvenile and b) adult grey-headed albatrosses tracked from Bird Island, South Georgia, at-sea distribution with pelagic longline fishing effort averaged over the 2010–2018 period. A bycatch hotspot for grey-headed albatrosses was reported in ICCAT subareas 6, 7 and 8 for April–June 1997–2015 (Inoue et al., 2012; Katsumata et al., 2017), and for July–September 1997–2009 (Inoue et al., 2012).

longline effort in ICCAT subareas 6, 7 and 8 (up to 2.1 million hooks in May; Fig. 3b), and dominated by the Japanese, South Korean and Taiwanese fleets in the southeast Atlantic in May–June (Figs. 4a & 5a), and by the Taiwanese fleet in the southwest Indian Ocean in June–July (Figs. 4a & 5a). Juveniles also overlapped to some extent with the Malaysian, Namibian, Seychellois, and Spanish fleets (Fig. 5a). Adults also overlapped with the Taiwanese fleet in the southwest Indian Ocean, predominately in June–August (Figs. 4b & 5b), and to a lesser extent with the Japanese, South Korea and Taiwanese fleets in the southeast Atlantic (mainly in June; Figs. 4b & 5b), and with the Chinese, Taiwanese and Vanuatuan fleets in the southwest Pacific Ocean (mainly in August; Figs. 4b & 5b). However, overlap scores with pelagic longline effort of tracked adults were much lower than those of juveniles (21–22 [jackknife range: 17–22] hooks $\times 10^3$ in June–August; Fig. 5b). Jackknifing of overlap scores revealed that bycatch risk was consistently higher for juveniles than adults in months of highest overlap (May–June; Fig. S3). Thus, although the sample size for juveniles was lower (Fig. 2), overlap scores were robust to the selection of individuals within our tracked sample.

4. Discussion

By comparing the at-sea distributions of juveniles and adults, we show that a reported bycatch hotspot for grey-headed albatrosses in the

southeast Atlantic corresponds to a previously unknown staging area used by juveniles fledging from the largest global population of this endangered species. These results highlight the importance of understanding within-population variation in movement patterns and are discussed in the context of focusing efforts on fisheries-bycatch mitigation.

4.1. Life-history stage and at-sea distributions

The most striking difference in the at-sea distributions of adults and juveniles was in May–June, corresponding to the period of dispersal at the end of breeding. During this time, juveniles travelled rapidly northeast from the natal colony, while adults made use of more southerly regions around South Georgia, the southwest Indian and Pacific Oceans. While the tracking data do not represent the movements of all individuals, juveniles used this narrow dispersal corridor in all three study years, suggesting that this route is important for the majority of birds from this population. Directed initial flight is common to juveniles of other albatross and petrel species (Weimerskirch et al., 2006; Gutowsky et al., 2014; de Grissac et al., 2016), and suggests their initial path is guided by an innate compass (Åkesson and Weimerskirch, 2005; de Grissac et al., 2016), which may help individuals reach distant foraging areas and reduce competition for resources between age classes (Gutowsky et al., 2014; Frankish et al., 2020). After these first few

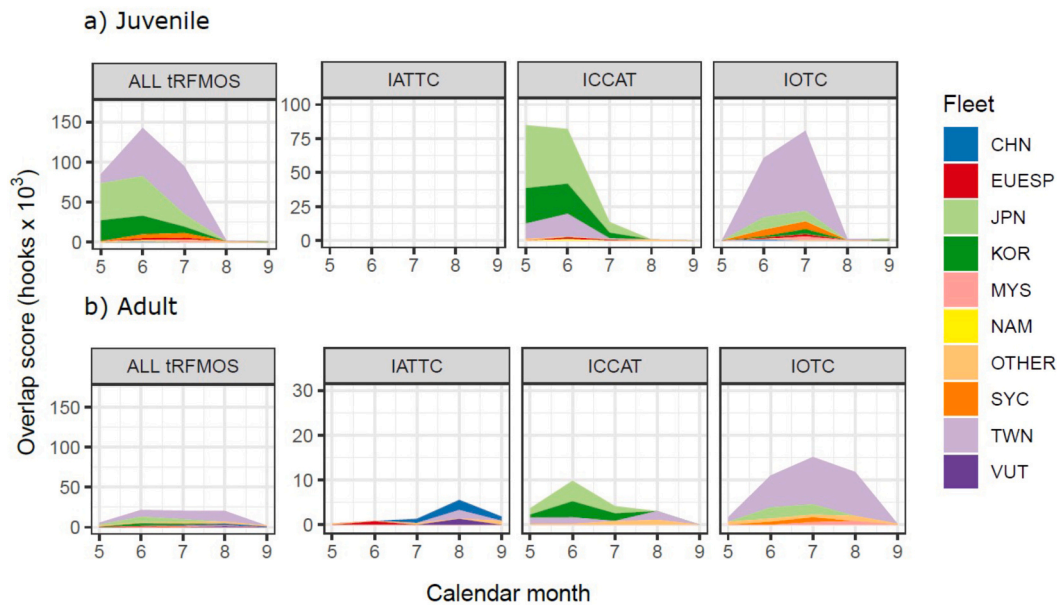


Fig. 5. Stacked overlap scores (hooks·10³; see Tables S2 & 3 for exact values) of a) juvenile and b) adult grey-headed albatrosses tracked from Bird Island, South Georgia, with pelagic longline fishing effort by tuna regional fisheries management organization (tRFMOS; IATTC = Inter-American Tropical Tuna Commission, ICCAT = International Commission for the Conservation of Atlantic Tunas, IOTC = Indian Ocean Tuna Commission) and fleet (CHN = China, EUESP = Spain, JPN = Japan, KOR = South Korea, MYS = Malaysia, NAM = Namibia, SYC = Seychelles, TWN = Taiwan, VUT = Vanuatu). Overlap with fleets from the Western and Central Pacific Fisheries Commission (WCPFC) was minimal and not included in this figure (Tables S2 & S3). Note that the scale of the y-axis differs for juveniles and adults.

months, nearly all juveniles continued east, mirroring two of the three migration strategies used by non-breeding adults: movement to wintering sites in the southwest Indian Ocean and circumpolar migrations (Croxall et al., 2005). One individual however returned towards South Georgia, thus adopting the third strategy of nonbreeding adults - remaining within the breeding range - and it therefore seems likely that individual exploration during the first year post-fledging determines foraging specializations used by adult grey-headed albatrosses throughout their lifetime, as in Cory's shearwaters (*Calonectris borealis*) Campioni et al. (2020).

4.2. Implications for overlap with pelagic longline fishing effort

As a result of their divergent movement patterns, adults and juveniles varied in the extent to which they overlapped with pelagic longline effort. In areas with high fishing intensity, birds are more likely to encounter and be caught by fishing vessels (Jiménez et al., 2016). Hence it can be assumed that juveniles have a higher mortality risk than adults, which may be compounded by their naïve foraging behavior. Some studies suggest juveniles may scavenge disproportionately behind vessels because of lower foraging efficiency, or that they are less able to avoid fishing gear (Österblom et al., 2002; Bregnballe and Frederiksen, 2006). However, age-specific variation in distribution appears to be the main driver of observed age-specific susceptibility to bycatch in seabirds at a global level (Gianuca et al., 2017). Soon after fledging (May–June), the tracked juveniles in our study reached the southern limit of high-intensity fishing effort in the southeast Atlantic, including the reported bycatch hotspot for this species in ICCAT subareas 6, 7 and 8 (Inoue et al., 2012; Katsumata et al., 2017). Although the age-class of bycaught birds in this region is unknown, tracked adults remained largely south of 40°S, and hence it is almost certain that a substantial proportion of the grey-headed albatrosses killed in this region are juveniles, and possibly immatures, from South Georgia. Indeed, immature albatrosses can have distributions intermediate to those of juveniles and adults, although more tracking data are required to determine if that is the case for this particular population. There is also the possibility that some birds killed in the bycatch hotspot are from breeding sites in the Indian Ocean (Nel

et al., 2001; Clay et al., 2016). However, given that juveniles in this study dispersed eastwards following prevailing winds, it may be that juveniles from other populations fledge in a similar direction and consequently use other oceanic regions in May–June (southwest Indian Ocean, Pacific Ocean). In addition, our overlap analyses identified two other fleets of major concern: Taiwan and South Korea in the same region in May–June, and Taiwan in the southwest Indian Ocean in June–July. There are some reports of bycaught grey-headed albatrosses in these regions by both fleets, but observer coverage is variable and generally low (Taiwan: 3–10.4% and South Korea: 7–24%; Huang, 2017; Kim et al., 2019), and seabird mortality will therefore be greatly underestimated. From August–September onwards, a greater proportion of the tracked juveniles travelled southeast towards areas of lower pelagic longline fishing effort, and so bycatch risk probably reduced to levels in line with those of the tracked adults (Figs. 2 and 3). Finally, our sensitivity analysis indicated that overlap scores varied little according to the subset of tracked individuals that were included in the analysis, suggesting that sample sizes were adequate to robustly assess relative bycatch risk of juveniles and adults from this population during the period of highest risk (May–September).

4.3. Conclusions and recommendations

Here we identify high overlap between the distribution of juvenile grey-headed albatrosses during the first months post-fledging and three major pelagic longline fleets: Japan, South Korea and Taiwan. Our results therefore confirm that a major bycatch hotspot reported by Japanese fisheries observers in the southeast Atlantic Ocean (Inoue et al., 2012; Katsumata et al., 2017) is likely to be of juveniles, and potentially also immatures, from South Georgia. Given the continued decline of this globally-important population, reducing bycatch by these fleets would play a crucial role in reducing extinction risk, especially as poor juvenile and immature survival will suppress recruitment rates (Pardo et al., 2017). We thus strongly recommend improved monitoring of bycatch rates, introduction of mandatory best-practice seabird-bycatch mitigation, and close compliance-monitoring either by independent observers or by using tamper-proof cameras on these vessels in the areas and

periods of greatest overlap. In addition, more support should be given to NGOs (e.g. The Albatross Task Force of BirdLife International) and governmental regulatory bodies to engage in outreach activities that raise awareness among key stakeholders of seabird bycatch, and provide training for crew in use of mitigation measures (Da Rocha et al., 2021). Finally, we encourage further tracking of under-studied life-history stages in other seabirds with high bycatch susceptibility.

CRediT authorship contribution statement

Caitlin K. Frankish: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Cleo Cunningham:** Conceptualization, Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition. **Andrea Manica:** Methodology, Software, Validation, Supervision, Writing – Review & Editing. **Thomas A. Clay:** Methodology, Software, Validation, Writing – Review & Editing. **Stephanie Prince:** Writing – Review & Editing. **Richard A. Phillips:** Conceptualization, Writing – Original Draft, Writing – Review & Editing, Supervision, Funding acquisition.

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.

Acknowledgements

We are grateful to all the fieldworkers involved in the device deployment and retrieval and to Andy Wood for database support. This study represents a contribution to the Ecosystems component of the British Antarctic Survey Polar Science for Planet Earth Programme, funded by NERC. The tracking devices were funded by the David and Lucile Packard Foundation, through the BirdLife International Global Seabird Programme, and by the South Georgia Heritage Trust, and the Friends of South Georgia Island. We also wish to express gratitude to the National Research Institute of Far Seas Fisheries (NRIFSF) for useful discussions, and in particular, Dr Daisuke Ochi. Thanks also to Dr Yasuko Suzuki of BirdLife International for useful advice. CFK was supported by a studentship co-funded by NERC (Grant Number: NE/L002507/1) and the Government of South Georgia and the South Sandwich Islands, with CASE funding from the Royal Society for the Protection of Birds (RSPB).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2021.109288>.

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