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### ► To cite this version:

Aymeric Fromant, Julien Collet, Cécile Vansteenbergh, Raphaël Musseau, Dominique Filippi, et al.. Fine-scale behaviour and population estimates of endangered sooty albatross suggest low exposure (while not excluding high sensitivity) to bycatch. *Marine Ecology Progress Series*, 2024, 10.3354/meps14719 . hal-04783517

**HAL Id: hal-04783517**

**<https://hal.science/hal-04783517v1>**

Submitted on 14 Nov 2024

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# Fine-scale behaviour and population estimates of endangered sooty albatross suggest low exposure (while not excluding high sensitivity) to bycatch

Aymeric Fromant<sup>1,\*</sup>, Julien Collet<sup>1</sup>, Cécile Vansteenbergh<sup>1</sup>, Raphaël Musseau<sup>2</sup>, Dominique Filippi<sup>3</sup>, Karine Delord<sup>1</sup>, Christophe Barbraud<sup>1</sup>

<sup>1</sup>Centre d'Etudes Biologiques de Chizé, UMR7372 CNRS – La Rochelle Université, 79360 Villiers en Bois, France

<sup>2</sup>BioSphère Environnement, 52 quai de l'Estuaire, 17120 Mortagne-sur-Gironde, France

<sup>3</sup>Sextant Technology, Ltd., Wellington 6012, New Zealand

**RPH: Fromant et al.: Low exposure of albatross to bycatch**

\*Corresponding author: aymericfromant@yahoo.fr

**ABSTRACT:** Recent developments in assessing species-specific seabird bycatch risks have demonstrated that fine-scale approaches are essential tools to quantify interactions with fishing vessels and to understand attraction and attendance behaviours. Matching boat movement with bird tracking data specifically allows us to investigate seabird–fisheries interactions for cryptic species for which on-board information is critically lacking. The sooty albatross *Phoebastria fusca* overlaps with fisheries throughout its range and is known to be vulnerable to incidental bycatch. Combining radar detectors, GPS and behavioural data from individuals from the Crozet Islands and boat locations during the incubation period, we investigated interactions of sooty albatrosses with fisheries in the southern Indian Ocean. Individuals foraged mostly in sub-tropical international waters, where they only encountered a small number of boats, all reporting to the Automatic Identification System (AIS). The low interaction rate during this period may suggest that sooty albatrosses are not strongly attracted to fishing vessels, and that attraction rates may vary between populations. However, this result should be interpreted with caution due to the low sample size and fishing effort during the study period, as these observations may conceal a higher bycatch risk during intense fishing effort and/or energetically demanding periods. The conservation status of this species requires further data to be collected throughout the annual cycle to provide an accurate assessment of the threat.

**KEY WORDS:** *Phoebastria fusca* · Fishery interaction · Fishing vessel · Risk assessment · Crozet Island · Automatic Identification System · Radar detecting device

## 1. Introduction

Due to the worldwide impacts of anthropic activities on oceanic ecosystems, seabirds are one of the most threatened groups of birds (Croxall et al. 2012, Dias et al. 2019). Facing threats both on land and at sea, more than half of all seabird species have declining trends, and a third of all species are globally threatened (BirdLife International 2022). Incidental bycatch (hereafter bycatch) from fisheries has clearly been identified to be one of the major threats to seabirds at sea, with large-scale longline fisheries having the greatest impact in terms of severity and scope (Dias et al. 2019). Despite the improvement in implementation of mitigation regulations over the last decades, seabirds still suffer from substantial bycatch risks (Votier et al. 2023).

43 Effective mitigation measures have been implemented for longline vessels, such as  
44 discard management (Bull 2007), hook-shielding devices (Sullivan et al. 2018), night setting  
45 (Brothers et al. 1999), bird-scaring lines (Domingo et al. 2017) and weighted branch lines  
46 (ACAP 2017, Paterson et al. 2019). Yet, the absence of population recovery for some species  
47 suggests that the implementation of mitigation measures remains relatively inadequate (Pardo  
48 et al. 2017), although other factors such as climate change, disease or invasive species may be  
49 involved (e.g. Jaeger et al. 2018). Our understanding of interaction processes is particularly  
50 limited for cryptic species for which the lack of knowledge on bycatch rates and interaction  
51 behaviour is scarce. Obtaining detailed information from the fishing industry can be  
52 challenging owing to low coverage of vessels by official observers among fisheries (Winnard  
53 et al. 2018). Therefore, increasing research effort to better understand seabird behaviour  
54 related to industrial fishing activities is needed to adapt conservation measures and work  
55 towards their effective compliance.

56 Until recently, bycatch risk was traditionally assessed through the coarse overlap  
57 estimates between fishing effort and seabird foraging area over large spatial and temporal  
58 scales (Clay et al. 2019, Heerah et al. 2019). Although this approach provides useful  
59 information to infer risk assessments at the population level and through the life cycle of a  
60 species, the absence of fine-scale data limits our understanding of when and how seabirds are  
61 exposed to bycatch. In particular, this method does not discriminate actual overlap versus  
62 interaction rate (i.e. theoretical vs. real risk), which may be misleading in assessing threats  
63 and subsequent mitigation measures. The possibility to access the publicly available  
64 Automatic Identification System (AIS), providing the locations and types of all declared  
65 vessels, has recently become the most suitable solution to obtain accurate information on the  
66 actual time seabirds spend interacting with fishing boats (Winnard et al. 2018). This new  
67 approach appears to be especially relevant for providing fine-scale bycatch risk assessments  
68 for species ranging outside national exclusive economic zones (EEZs), where mitigation  
69 measures are particularly difficult to implement (Dias et al. 2019). In addition, deploying  
70 radar-detecting devices on seabirds has been shown to be a necessary complementary  
71 approach to detect any vessels not using AIS (Weimerskirch et al. 2018a), such as illegal and  
72 unregulated fishing boats. These fine-scale approaches have successfully been applied to  
73 investigate bycatch risks for other seabird species (Weimerskirch et al. 2020, Corbeau et al.  
74 2021a), providing crucial information on their interactions with and behaviour towards fishing  
75 vessels, and helping to assess the proportion of illegal vessels encountered. However, while  
76 these studies focused on relatively abundant and conspicuous species, such as wandering  
77 albatrosses *Diomedea exulans*, which are strongly attracted to fishing vessels, knowledge of  
78 more cryptic species has remained limited.

79 The sooty albatross *Phoebastria fusca*, listed as **Endangered by the IUCN**, was recently  
80 classified as being one of the procellariiform species most exposed to bycatch risks (Reid et al.  
81 2023), confirming the potential contribution of fisheries bycatch mortality to the observed  
82 multi-decade population decline throughout the Southern Ocean (Cuthbert & Sommer 2004,  
83 Delord et al. 2008, Rolland et al. 2010, Schoombie et al. 2016, Weimerskirch et al. 2018b).  
84 Although the sooty albatross is described as a species interacting only rarely with fishing  
85 vessels (Griffiths 1982, SIOFA 2024, **unpublished French Southern Breeding Seabird Survey**  
86 **database**), emphasising the need to quantify fine-scale seabird–fishery interactions for such  
87 species, this may partly reflect a sampling bias as there is direct evidence that some  
88 individuals are victims of bycatch (Gales et al. 1998, Huang & Liu 2010, unpublished French  
89 Southern Breeding Seabird Survey database). Using AIS, Banda et al. (2024) demonstrated  
90 that sooty albatrosses from Marion Island displayed much lower exposure and attraction to  
91 (declared) fishing vessels compared to other species in the Southern Ocean, such as the

92 wandering albatross (Corbeau et al. 2021a, Carneiro et al. 2022) or the white-chinned petrel  
93 *Procellaria aequinoctialis* (Banda et al. 2024). However, the apparent discrepancy between  
94 the behaviour of sooty albatrosses and their exposure to bycatch may fade when considering  
95 the combined effects of the small population and the life history of the species. In particular,  
96 sooty albatrosses are biennial breeders with a single-egg clutch, meaning that populations  
97 from this species rely on a long-term high survival rate to maintain a stable, small population.  
98 In this context, any bycatch event, even with a low exposure risk, may have a significant  
99 impact at the population level (Dillingham & Fletcher 2011). Therefore, the possibility to also  
100 test for interactions with fishing boats that are undeclared to the AIS system (which could  
101 comprise up to 30% of fishing boats in the southwestern Indian Ocean) seems important.

102 In addition, geographical differences in foraging habitats can also lead to variations in  
103 overlap and attraction to fishing vessels (Soriano-Redondo et al. 2016, Cianchetti-Benedetti et  
104 al. 2018). For example, wandering albatrosses from the Crozet Islands appeared to attend  
105 boats for a shorter duration than conspecifics from the Kerguelen Islands, but encountered  
106 more illegal fishing vessels due to their specific foraging habitat (Corbeau et al. 2021b).  
107 These results exemplify the need to develop bycatch risk assessments for sooty albatrosses at  
108 the population level.

109 The Crozet Islands historically hosted one of the largest populations of sooty  
110 albatrosses in the southern Indian Ocean, although the number of breeding pairs has declined  
111 by more than 81% since 1980 (trend extrapolated from the population surveyed at Île de la  
112 Possession) (Fig. 1; Delord et al. 2008, Weimerskirch et al. 2018b). Therefore, it is crucial to  
113 assess the bycatch risk to which this population is exposed, which necessitates quantifying  
114 and understanding interactions at fine spatial and temporal scales. Combining seabird GPS  
115 tracking data, radar detector and vessel AIS data, this study aimed to (1) obtain accurate  
116 information (occurrence and location) on interactions between vessels and sooty albatrosses  
117 from the Crozet Islands during the incubation period, with a particular focus on fisheries  
118 (including illegal fishing vessels); and (2) investigate the behaviour of individuals  
119 encountering and attending boats (fishing vessels or non-fishing vessels) by determining if the  
120 presence of a vessel influences their searching activity.

## 121 2. Materials and Methods

### 122 2.1. Study site and study species

123 The study was carried out at Île de la Possession (Crozet Islands, southern Indian  
124 Ocean; 46° S, 51° E) between November and December 2022. In the past, the Crozet  
125 Archipelago, situated between the Sub-Antarctic and the Antarctic Polar fronts, hosted nearly  
126 16% of the global population of sooty albatrosses (Delord et al. 2008, 2013). The population  
127 of sooty albatrosses in the whole archipelago (5 main islands) was last estimated by Jouventin  
128 et al. (1984) to be 2335 breeding pairs. Since then, the population of Île de la Possession has  
129 been used as a reference site to estimate the population trend of the Crozet Archipelago  
130 (Delord et al. 2008). This population experienced an important decline between 1981 and  
131 2000 at an average rate of 4.2% per year, followed by a slower decline of 1.9% per year over  
132 the last 2 decades (Fig. 1). Assuming that the populations on all islands in the archipelago  
133 followed the same 81% decrease between 1980–81 and 2022–23, it would suggest that the  
134 Crozet population has been reduced to 444 annual breeding pairs.

135 The sooty albatross is present at Crozet between late August and late June, incubating  
136 a single egg from early October to mid-December, with chicks fledging in late May  
137 (Weimerskirch et al. 1986). During the incubation period, males and females alternate  
138 incubation shifts, with foraging trips lasting on average 11 d (Weimerskirch et al. 1986).

## 139 **2.2. Tracking data and fishing effort**

140 A total of 13 adult sooty albatrosses were equipped with XAIS-Sputnik loggers  
141 developed by Sextant Technology (recording location, wet/dry information and equipped with  
142 a radar detector) during the incubation period in order to record their at-sea movements and  
143 behaviour. The devices were programmed to record locations every 10 min for at least 1 trip  
144 during late incubation. Individuals were captured on the nest at the estimated end of their  
145 incubation shift, and loggers were attached to the back feathers using waterproof tape (Tesa  
146 4651). To limit the duration of handling, the equipped individuals were not weighed in the  
147 present study; however, the total mass of logger attachments (52 g) was estimated to  
148 correspond to 2.1% of body mass (average body mass = 2.5 kg; Marchant & Higgins 1990).  
149 Handling duration was  $8.6 \pm 1.4$  min for deployment, and  $4.4 \pm 2.5$  min for retrieval.

150 AIS data of vessels operating in the study area were downloaded from Global Fishing  
151 Watch (<https://globalfishingwatch.org>) using the R package 'gfwr' (Merten et al. 2016). The  
152 Global Fishing Watch website provides tracking data from available AIS and combines  
153 information acquired through vessel monitoring systems that are made available through  
154 partnerships with governments. For each vessel, location, identification name, type of vessel  
155 (fishing or non-fishing) and activity were obtained for the same temporal and spatial extent as  
156 the birds were tracked. GPS loggers deployed on sooty albatrosses were combined with a  
157 radar detector. This system was developed to detect vessels that do not use AIS, in particular  
158 illegal fishing vessels. This method allows the detection of vessels with radar emitting within  
159 a 5 km range from equipped birds (Weimerskirch et al. 2018a). Therefore, vessels with a  
160 deactivated AIS will only be recorded if there is a close encounter.

161 Fishing effort from longline fisheries was provided by the Southern Indian Ocean  
162 Fisheries Agreement (SIOFA; sub-areas 1, 2, 3a and 3b) and the Commission for the  
163 Conservation of Antarctic Marine Living Resources (CCAMLR; sub-areas 58.6 and 58.7).  
164 The number of hooks deployed was pooled by month and sub-areas to determine the spatio-  
165 temporal variation in fishing effort in the area used by sooty albatrosses from Île de la  
166 Possession.

## 167 **2.3. Behavioural and data analysis**

168 For tracking data of sooty albatrosses, all on-land locations were removed from GPS  
169 tracks, and locations were interpolated with a time step of 10 min to correct for any unequal  
170 sampling frequencies. For each complete foraging trip, the following basic parameters were  
171 determined: trip duration (h), total horizontal distance travelled (km) and maximum distance  
172 from the colony (km). Sooty albatross locations and AIS data were then spatio-temporally  
173 matched following Weimerskirch et al. (2020), resulting in a data set with each bird location  
174 corresponding with information about the nearest vessel transmitting AIS. Distance thresholds  
175 of 100 km (boat seascape), 30 km (boat encountered) and 5 km (boat attended) were used to  
176 classify and determine the behaviour of sooty albatrosses when foraging within each of these  
177 categories (Weimerskirch et al. 2020). Within the 100 km range, the boat was considered to  
178 be available in the seascape of the individual, while the 30 km range corresponds to the  
179 maximum distance at which an albatross can visually detect a vessel (Collet et al. 2015). The  
180 5 km threshold relates to the distance at which seabirds perform specific foraging behaviours  
181 when reaching this proximity of a vessel (Collet et al. 2015, Corbeau et al. 2019,  
182 Weimerskirch et al. 2020).

183 Expectation maximization binary clustering (EMBC) was used to infer the at-sea  
184 foraging behaviour of sooty albatrosses using the R package 'EMbC' (Garriga et al. 2016).  
185 Using travel speed and turning angle between subsequent locations, this method classifies the



186 movement of seabirds into 4 different categories: travelling–commuting (high speed, low  
187 turn), extensive searching (high speed, high turn), intensive searching (low speed, high turn)  
188 and resting on the water (low speed, low turn). This method is well suited to interpreting  
189 ecologically meaningful behaviours for procellariiform species, including albatrosses (de  
190 Grissac et al. 2017).

191 In addition, behavioural information was collected using wet and dry data, with the  
192 proportion of time spent submerged being a proxy for feeding events. When the device is in  
193 contact with seawater, the logger records if the device is wet or dry every second for the next  
194 2 min. It then restarts the process if the device is still submerged after 2 min. This method  
195 allows for the saving of battery and memory space while recording high-resolution data. The  
196 data set was merged with the bird location file to obtain a percentage of time spent submerged  
197 per location. This information was then combined with the EMBC classification outputs to  
198 refine the interpretation of sooty albatross foraging behaviour.

199 All processing and statistical analyses were conducted in the R statistical environment  
200 (R Development Core Team 2022). For each trip, the number of vessels (fishing or non-  
201 fishing) in the seascape, encountered or attended, was determined. The duration during which  
202 individuals stayed within 100 or 30 km for the instances that ended up with an encounter or an  
203 attendance, or neither, were compared using non-parametric Mann-Whitney *U*-tests.  
204 Statistical comparisons of the 4 behavioural classes between the different radius distances  
205 (100, 30 and 5 km) were not possible because of the small number of boat attendances (4  
206 instances).

## 207 **3. Results**

### 208 **3.1. Foraging trips**

209 A total of 12 devices were retrieved out of the 13 deployed on breeding sooty  
210 albatrosses (recovery rate = 92.3%). The last device was never retrieved due to breeding  
211 failure. In addition, no data were recovered from 1 device, likely due to waterlogging.  
212 Successful devices collected tracking data for 11 trips at the end of the incubation period (11  
213 individuals; between 27 November and 16 December). For 2 individuals, an additional 3 trips  
214 were recorded during early chick-rearing (between 19 and 25 December) (Table 1). From the  
215 11 individuals tracked (14 foraging trips), a total of 2682 h of tracking were recorded,  
216 corresponding to 112 d at sea.

217 Adult sooty albatrosses travelled on average  $5285 \pm 1320$  km per foraging trip during  
218 incubation, for a mean duration of  $229 \pm 49$  h at sea, and a mean maximum distance from the  
219 colony of  $1340 \pm 340$  km. The 3 trips during early chick-rearing were much shorter, with a  
220 mean travelled distance of  $908 \pm 434$  km, a mean duration of  $52 \pm 31$  h and a mean maximum  
221 distance from the colony of  $442 \pm 30$  km. During incubation, all individuals travelled further  
222 than the extent of the EEZ of the Crozet Islands, foraging mostly north of the Sub-Antarctic  
223 (SAF) and Subtropical Fronts (STF) (Fig. 2). Sooty albatrosses allocated proportionally more  
224 time searching (intensive and extensive searching) when they were in sub-tropical open  
225 waters (25.0%) compared to when foraging in sub-Antarctic waters (16.8%).

### 226 **3.2. Boatscape description**

227 During the period when sooty albatrosses were tracked (27 November to 25  
228 December), 310 vessels were identified using AIS data in the study area, including 26 fishing  
229 vessels (8.4%). The great majority of ship activity was concentrated in a large area north of –  
230 39°, while fishing activity was mostly restricted south of this zone (Fig. A1 in the Appendix).

231 Sooty albatrosses were recorded 44 times within 100 km of a vessel, of which 14  
232 corresponded to fishing vessels (31.8%) (Table 1). Of these instances, individuals were  
233 recorded 16 times (6 different individuals) within 30 km of a vessel (5 fishing vessels;  
234 31.3%), and 4 of these encounters (3 different individuals) ended up with an individual  
235 recorded within 5 km of a vessel (1 fishing vessel; 25%) (Fig. 3, Table 1). For 3 of the 14  
236 trips, the individuals were never recorded within 100 km of a vessel (Table 1).

237 Two vessels were detected using radar detection devices deployed in combination with  
238 tracking devices attached to the birds. They both matched a vessel attendance (individual  
239 within 5 km) detected with the vessel AIS (Fig. 3). One of these was a fishing vessel. There  
240 was no detection of any vessel that was not identified within the Global Fishing Watch AIS  
241 database.

242 For each instance of sooty albatrosses being within 100 km of a vessel, individuals  
243 were within this zone on average for  $4.9 \pm 3.5$  h ( $n = 44$ ). They remained within 30 km of a  
244 vessel for  $1.7 \pm 1.2$  h ( $n = 16$ ), and within 5 km for  $20 \pm 0$  min ( $n = 4$ ). There were 7 cases in  
245 which individuals never went within 30 km of a vessel (6 different individuals). In these  
246 instances, sooty albatrosses spent significantly less time within 100 km compared to the cases  
247 for which individuals were found within 30 km of a vessel ( $3.9 \pm 3.2$  vs.  $6.7 \pm 3.5$  h; Mann-  
248 Whitney  $U = 350$ ,  $p = 0.002$ ). However, there was no difference in the duration spent within  
249 100 km of a vessel between cases with individuals recorded within 30 km but never entered  
250 within 5 km, and cases when individuals were found within 5 km of a vessel ( $6.9 \pm 3.5$  vs.  $5.9$   
251  $\pm 3.7$  h; Mann-Whitney  $U = 18.5$ ,  $p = 0.543$ ). Similarly, there was no difference between  
252 these 2 groups for the duration spent within 30 km of a vessel ( $1.5 \pm 1.3$  vs.  $1.7 \pm 0.9$  h;  
253 Mann-Whitney  $U = 29.5$ ,  $p = 0.540$ ).

### 254 3.3. Sooty albatross foraging behaviour and boat encounters

255 When within 100, 30 or 5 km, sooty albatrosses did not present any clear change in  
256 behaviour. The EMBC model appeared to indicate no clear difference in the proportion of  
257 time searching when individuals were within 100, 30 or 5 km of a vessel compared to when  
258 farther away from a vessel (Fig. 4). Similarly, there was no clear pattern in time spent wet  
259 (proxy of feeding event; Fig. 4), nor in terms of speed or if individuals aimed towards or  
260 followed the vessels during encounters (within 30 km) (Figs. 3 & 5). In the 4 instances for  
261 which the birds were within 5 km of a boat, none of the individuals stopped (no wet data), and  
262 all of them remained no more than 20 min within this distance of the vessel.

## 263 4. Discussion

264 The present study provides detailed data about the at-sea distribution of sooty  
265 albatrosses during the incubation period, quantifying and mapping boat encounters from GPS,  
266 AIS and radar detectors, and contributing to a better understanding of their attraction  
267 behaviour towards vessels. The low encounter and interaction rates with fishing vessels  
268 during this period may suggest that sooty albatrosses are not strongly attracted to these boats,  
269 and therefore might not be exposed to a high risk of bycatch. However, in the present study,  
270 the small sample size and the low rate of interaction should not dismiss the substantial  
271 impacts that a low number of bycatch events can cause on small populations, such as that of  
272 the Crozet Archipelago. In addition, the lack of data during periods of high fishing effort,  
273 and/or of high energetic demand for individuals (such as chick rearing or moulting),  
274 demonstrates the importance of fully assessing bycatch risk throughout the whole annual  
275 cycle.

### 276 4.1. At-sea distribution and exposure to fishing vessels

277 At-sea distribution data of breeding albatrosses is crucial for their effective  
278 conservation, as these species forage over extensive areas comprising a mix of multiple EEZs  
279 and High Seas (e.g. Thiebot et al. 2014). During the incubation period, sooty albatrosses from  
280 Île de la Possession foraged mostly in open oceanic waters north of the STF, comparable to  
281 individuals from Marion Island (Schoombie et al. 2017, Banda et al. 2024). In this area, sooty  
282 albatrosses from both populations overlap with longline and trawling fisheries that have  
283 previously documented seabird bycatch (including sooty albatrosses from Île de la Possession;  
284 unpublished French Southern Breeding Seabird Survey database). However, in the present  
285 study, and similarly to that of Banda et al. (2024), there were limited numbers of fishing  
286 vessels present in the seascape of the birds, ultimately leading to few encounters. The austral  
287 summer is the period during which the fishing effort is the lowest in this area, with 8 times  
288 fewer hooks deployed in December compared to August (Fig. 6). Because albatrosses cannot  
289 detect vessel presence at distances greater than 30 km (Collet et al. 2015, Pirodda et al. 2018),  
290 it is the proportion of fishing boats within the seascape (100 km) that determines the  
291 probability of potential encounters. The low probability of encounter in December is  
292 highlighted by the small proportion of individuals that were within 30 km of a fishing vessel  
293 (27% in the present study, 20% in Banda et al. 2024).

294 Nonetheless, despite a low number of interactions with fishing vessels at the  
295 individual level, bycatch risk can be substantial when considering the whole population.  
296 Based on the current estimate of 444 breeding pairs for the Crozet Island population,  
297 extrapolating the probability of interaction (0.09 per day and individual) would suggest that  
298 between 2 and 3 individuals are likely to be within 5 km of a fishing vessel each day during  
299 the 70 d of the incubation period (see Text A1 for calculation details). In addition, assuming  
300 that the probability of interaction is proportional to the fishing effort, this number might rise  
301 to 20–25 ind. d<sup>-1</sup> in winter (June–September), when sooty albatrosses from the Crozet Islands  
302 spend more time in sub-tropical waters (Delord et al. 2013). For biennially breeding species,  
303 mortalities from all sources (including bycatch) should not exceed 0.015 times the number of  
304 breeding pairs to maintain a viable population, which corresponds to 6.7 ind. yr<sup>-1</sup> for the sooty  
305 albatross population from Crozet (Dillingham & Fletcher 2011). The unusually low adult  
306 survival observed for this population (0.888, Rolland et al. 2010, Schatz et al. unpublished  
307 data, compared to 0.924 for the closely related light mantled sooty albatross *Phoebetria*  
308 *palpebrata* at Macquarie Island, Clelland et al. 2021), the negative relationship between adult  
309 survival and tuna longline fishing effort (Rolland et al. 2010) and the absence of population  
310 recovery since the sharp collapse observed in the 1980s suggest that individual mortality is  
311 still exceeding this rate. Although these interaction rate estimates should be interpreted with  
312 caution due to the small sample size, this information highlights that further work is needed to  
313 fully determine the effects of bycatch on the sooty albatross population trend at Crozet Island.

## 314 4.2. Foraging behaviour and attraction to vessels

315 Both onboard boat observations and tracking data have demonstrated substantial  
316 seabird inter-species variations in occurrence and interaction behaviour with fishing vessels  
317 (Hudson & Furness 1989, Chérel et al. 1996, Collet et al. 2017a, Corbeau et al. 2021a).  
318 Studies of albatross species strongly attracted to fishing vessels, such as wandering and black-  
319 browed albatrosses *Thalassarche melanophrys*, demonstrated that individuals exhibit  
320 attraction responses by clearly changing their trajectory towards the boat upon detecting it  
321 (Collet et al. 2015, 2017a). In the present study, there was no evidence that sooty albatrosses  
322 changed flight direction, or speed, when they were within 30 km of a vessel. The distance of  
323 30 km is interpreted as the maximum distance at which an albatross could visually detect a  
324 vessel, although this could be dependent on the flight height of the individual, and therefore  
325 could be species-specific (Collet et al. 2017a). However, the absence of any trajectory change



326 when closer than 30 km for the sooty albatross suggests that the difference in attraction  
327 towards boats compared to other species might not originate from a lower detection capacity.

328 When actively interacting with a boat, the behaviour of attending seabirds is similar to  
329 intense search events, with a lower speed and higher sinuosity (Torres et al. 2011, Bodey et al.  
330 2014). Birds attracted to boats usually stay within a close range for at least a couple of hours  
331 (Collet et al. 2017b), and spend more time on the water, which is interpreted as feeding  
332 attempts (Collet et al. 2015). Sooty albatrosses in the present study, as well as in Banda et al.  
333 (2024), did not exhibit obvious signs of attraction behaviour towards boats (fishing or non-  
334 fishing vessels). In both studies, individuals remained within 5 km of the boats for less than  
335 20 min, did not stop and appeared to simply fly past. Although not all seabirds necessarily  
336 interact with boats that they encounter (Torres et al. 2013, Sugishita et al. 2015, Collet et al.  
337 2017b), our results support the hypothesis that sooty albatrosses are less inclined to interact  
338 with fishing vessels than other species such as wandering albatrosses (Griffiths 1982).

339 Estimating attraction to fishing vessels using bird-borne radar detectors is recent  
340 (Weimerskirch et al. 2018a), and attraction rates have only been estimated for a few  
341 populations of seabird species. Fishing vessel encounter and attraction rates seem to vary  
342 between populations of wandering albatross, with encounter rates ranging from 55 to 85% and  
343 attraction rates from 43 to 73% across 4 populations (Corbeau et al. 2021a, Carneiro et al.  
344 2022). Our study suggests similar intra-specific variation in sooty albatrosses, albeit with  
345 lower sample sizes, with 20 and 27% encounter rates and 5 and 9% attraction rates at Marion  
346 and Crozet, respectively. Such intra-specific variation is puzzling and requires further study,  
347 but may be related to different past and current environmental constraints to which  
348 populations have been exposed.

349 Optimal foraging theory predicts that the prey preference, the aggressiveness of  
350 individuals and their dominance rank within a seabird aggregation could affect the decision of  
351 whether or not to join a foraging patch generated by a fishing vessel (Stephens & Krebs 1986,  
352 Giraldeau & Caraco 2000). Therefore, the apparent low interest of sooty albatrosses towards  
353 boats could arise from competitive exclusion. Larger and/or more aggressive individuals, such  
354 as wandering albatrosses, could prevent the smaller sooty albatrosses from joining seabird  
355 aggregations (Weimerskirch et al. 1993, González-Solís et al. 2000). As much as this  
356 behaviour could be an inherent trait of the species, this also could have been a result of a  
357 recent human-induced evolutionary mechanism. Indeed, the sharp decrease of the sooty  
358 albatross population in the 1980s at Île de la Possession coincides with the development of  
359 longline fisheries, and bycatch could have acted as a harvesting pressure whereby individuals  
360 more attracted to fishing vessels or more dominant in seabird aggregations were removed  
361 from the population. Such selective mortality would have had an effect on the interaction  
362 behaviour at the population level similar to what was theorised for the wandering albatross  
363 (Barbraud et al. 2013, Tuck et al. 2015).

364 However, even if the sooty albatross is or has become a less dominant species, or has a  
365 lower appetite for the food made available by fishing vessels, bycatch records confirm that  
366 this species is still attracted, even in a low proportion (Huang & Liu 2010). A previous study  
367 of interactions between longline vessels and seabirds recorded that sooty albatrosses were  
368 found to interact in 4% of the observations (Cherel et al. 1996). The fact that this species  
369 might only interact with fishing vessels occasionally could suggest that this behaviour is  
370 hardly detectable by short-term tracking surveys. Indeed, combining the present study and  
371 Banda et al. (2024), only 31 individuals were tracked, covering a few weeks at the end of the  
372 incubation period. Late November and early December also correspond to the period with the  
373 lowest fishing effort, suggesting that the absence of clear interaction behaviour could be an  
374 artefact of a low interaction rate, a low sample size and few fishing vessels present in the area

375 during the study period. In addition, attraction towards fishing vessels can vary seasonally,  
376 independently of the boat density. Factors such as low food availability and/or high energy  
377 requirements can influence seabirds by stimulating temporary high-risk behaviour (Bateson  
378 2002, Clark et al. 2020). Therefore, the information collected about sooty albatross attraction  
379 towards fishing vessels during the incubation period may conceal a higher bycatch risk during  
380 energetically demanding periods, such as chick-rearing, moulting or pre-breeding periods.

### 381 4.3. Conclusion and perspective

382 Feedback from the South Georgia longline fishery indicates that strict implementation  
383 of regulation measures, such as night-setting and line-weighting, has reduced seabird  
384 mortality to negligible levels (Collins et al. 2021). However, without 100% observer coverage  
385 enforced, the level of compliance and bycatch rates remain uncertain, in particular for  
386 fisheries operating outside EEZs where they are not legally obligated to report bycatch rates.  
387 Sooty albatrosses from the southern Indian Ocean forage mostly in the High Seas (present  
388 study, Delord et al. 2013, Schoombie et al. 2017, Heerah et al. 2019, Banda et al. 2024), and  
389 although the present study may suggest that this albatross species does not exhibit a strong  
390 attraction behaviour towards fishing vessels, some individuals are still victims of bycatch  
391 (Gales et al. 1998, Huang & Liu 2010, unpublished French Southern Breeding Seabird Survey  
392 database). In this context, it is crucial to determine if the interaction rate and attraction  
393 behaviour of sooty albatrosses change seasonally in accordance with food availability, energy  
394 requirements and fishing effort, and whether they vary between populations. The present  
395 study contributes to a better understanding of the at-sea behaviour of sooty albatrosses, and  
396 allows us to assess the risk of bycatch during the incubation period. Nevertheless, uncertainty  
397 remains about when and where sooty albatrosses are the most at risk, which implies that new  
398 data collection strategies and approaches should be developed. In particular, overcoming the  
399 challenges of investigating the behaviour of such species during the non-breeding period  
400 appears to be a priority to provide a reliable assessment of the actual bycatch risk that they are  
401 facing.

402

403 *Acknowledgements.* This study was funded by an Agreement on the Conservation of  
404 Albatrosses and Petrels (ACAP) Small Grant (Grant number 2020-15 to C.B.) and by Réserve  
405 Naturelle Nationale des Terres Australes Françaises (Célia Lesage). The fieldwork in Crozet  
406 was funded and logistically supported by IPEV (project 109 OrnithoEco). We thank  
407 Alexandre Vong, Jeanne Abbou, Célia Lesage (RN TAF), Nicolas Croizet (RN TAF),  
408 Clément Jaunas and Thomas Bobillier for their help in the field, and Henri Weimerskirch for  
409 his advice during preparation for the field work. We thank Dominique Filippi from Sextant  
410 Technology for his help with the start-up of XAIS loggers. This study is part of the long-term  
411 Studies in Ecology and Evolution (SEE-Life) program of the CNRS. We also thank Daphnis  
412 De Pooter (CCAMLR) and Pierre Peries (SIOFA) for assisting with the provision of the  
413 fishery data, and all data owners for their permission for the use of the data. The field  
414 procedures and manipulations on Crozet were approved by the Comité National de la  
415 Protection de la Nature and by the Préfet of Terres Australes et Antarctiques Françaises  
416 (permit numbers 2022-70 and 2022-84). We thank 3 anonymous reviewers for constructive  
417 comments on an earlier version of this paper.

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Table 1. Boats in seascape, encountered and attended by sooty albatrosses from Île de la Possession. Each row corresponds to one trip, indicating the number of instances this individual entered within 100, 30 or 5 km of a vessel (for all vessel types), and the total duration during which the individual was within this distance during the whole trip. The number and duration of instances individuals entered within 100, 30 or 5 km of a fishing vessel are indicated in brackets. All foraging trips were made during late incubation, except trips SA-111 (2), SA-114 (2) and SA-114 (3), which occurred during the early brooding stage (see Fig. 3)

Individual (Trip)	Trip duration (h)	<100 km		<30 km		<5 km	
		Instances (fishing vessel)	Duration (h) (fishing vessel)	Instances (fishing vessel)	Duration (h) (fishing vessel)	Instances (fishing vessel)	Duration (h) (fishing vessel)
SA-105	249	10 (1)	112.7 (1.7)	4 (0)	14.0 (0.0)	2 (0)	1.3 (0.0)
SA-108	316	5 (3)	74.0 (36.3)	3 (2)	10.7 (7.6)	1 (1)	0.7 (0.7)
SA-101	260	5 (1)	45.3 (3.7)	3 (0)	8.0 (0.0)	1 (0)	0.7 (0.0)
SA-106	243	6 (2)	56.0 (29.0)	2 (1)	5.0 (1.7)	-	-
SA-111 (1)	235	4 (2)	42.7 (19.4)	2 (1)	3.7 (2.7)	-	-
SA-111 (2)	62	2 (1)	28.7 (13.7)	2 (1)	6.7 (1.7)	-	-
SA-107	260	3 (1)	25.0 (4.0)	-	-	-	-
SA-104	237	4	42.7	-	-	-	-
SA-110	213	2 (1)	8.3 (5.3)	-	-	-	-
SA-114 (2)	78	2 (1)	10.0 (4.7)	-	-	-	-
SA-111 (3)	17	1 (1)	6.0 (6.0)	-	-	-	-
SA-112	157	-	-	-	-	-	-
SA-114 (1)	218	-	-	-	-	-	-
SA-103	136	-	-	-	-	-	-

1 **Fig. 1.** Annual number of breeding pairs of sooty albatrosses at Île de la Possession, Crozet  
2 archipelago. Orange dots correspond to annual ground counts of breeding pairs. The red lines  
3 indicate linear trends for the periods 1980–2000 and 2001–2023

4 **Fig. 2.** Foraging trips of sooty albatrosses from Île de la Possession, Crozet Islands. The thin  
5 black tracks correspond to foraging trips during the incubation period, while the thick black  
6 and white tracks (within the Crozet exclusive economic zone, EEZ) show the 3 trips in the  
7 early brooding stage. **Thick turquoise lines** — STF = Subtropical Front; SAF = Sub-Antarctic  
8 Front (Kim & Orsi 2014). The circular green shapes correspond to the exclusive economic  
9 zones (EEZs) of the Crozet Islands (**grey triangle**) and Marion and Prince Edward Islands  
10 (**grey square**). The dashed lines correspond to the SIOFA (yellow) and the CCAMLR (red)  
11 areas

12 **Fig. 3.** Positions of vessels within the seascape (<100 km; green circular patches), vessels  
13 encountered (<30 km; yellow circular patches) and vessels attended (<5 km; red circular  
14 patches) by sooty albatrosses (black tracks) from Île de la Possession. (A–D) The 4 cases for  
15 which an individual was within 5 km of a vessel. For each case, arrows indicate the travel  
16 direction of the individual and the vessel; the colour of the bird track corresponds to its speed,  
17 and the white dots show instances when the device was submerged (note that the green,  
18 yellow and red patches are representational only and are not to scale). Dark blue dashed  
19 outline: instances when the radar detection device detected the vessels (i.e. Cases A and C).  
20 Case A was the only instance for which a sooty albatross was within 5 km of a fishing vessel  
21 (trawler)

22 **Fig. 4. (a) Counts and (b) proportion** of behaviour of sooty albatrosses determined using an  
23 expectation maximization binary clustering (EMBC) model and proportion of time the device  
24 was submerged (red and white line). Travelling = high speed, low turn; resting = low speed,  
25 low turn; extensive searching = high speed, high turn; intensive searching = low speed, high  
26 turn. In (a), counts are not provided for locations >100 km because of the large number of  
27 data (>14000) compared to locations within 100 km

28 **Fig. 5. (a) Speed and (b) bearing** of sooty albatrosses towards vessels. In (b), an angle of 0°  
29 indicates that the individuals were heading towards the vessel, while 180° indicates that they  
30 were heading in the opposite direction

31 **Fig. 6.** Monthly fishing effort in the areas potentially used by sooty albatrosses from Crozet  
32 and Marion Islands. Each colour corresponds to the SIOFA (sub-areas 1, 2, 3a and 3b) and the  
33 CCAMLR (sub-areas 58.6 and 58.7) areas. The monthly fishing effort **was averaged** over 5 yr  
34 (2017–2022)

## 35 **Appendix**

36 **Fig. A1.** Tracks of vessels during the study period obtained from Global Fishing Watch.  
37 Tracks in red correspond to fishing vessels. **Grey ellipses:** exclusive economic zones (EEZs)  
38 of the Crozet Islands (grey triangle) and Marion and Prince Edward Islands. The dashed lines  
39 correspond to the SIOFA (yellow) and the CAMMLR (red) areas

### 40 **Text A1. Estimation of the number of individuals interacting with fishing** 41 **vessels per day**

42 In the present study, there was only 1 interaction with a fishing vessel during the 11  
43 foraging trips recorded in the incubation period (11 individuals) for a total of 105 d at sea.  
44 Therefore, for this data set, the number of interactions per day and per individual was  
45  $(1/11)/105 = 0.0009$ . For the whole Crozet population, the number of breeding pairs was

46 estimated at 444 in 2022–2023 (extrapolation obtained from the population monitored  
47 annually at Île de la Possession, see Section 2). For biennially breeding albatrosses, the  
48 estimated number of individuals per breeding pair is 7.3 (conservative estimate from  
49 [Dillingham & Fletcher 2011](#)), which corresponds to 3,241 sooty albatross individuals for the  
50 whole Crozet population. With 0.0009 interactions with fishing vessels per day and per  
51 individual, the total number of individuals interacting per day was estimated at 2.9 for the  
52 whole population during the incubation period. If we consider that the interaction rate is  
53 proportional to the fishing effort, the fact that the fishing effort is 8 times higher in August  
54 than December in the study area brings an estimate of about 23 individuals interacting per  
55 day. These estimates should be used with caution, as they are calculated from a small data set.  
56 This approach is used here to demonstrate that a small interaction rate can be potentially  
57 impactful at the population level.