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## Ocean sentinel albatrosses locate illegal vessels and provide the first estimate of the extent of nondeclared fishing

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2 **Albatrosses as Ocean Sentinels: from research to operational**  
3 **monitoring of Southern Ocean's fisheries**

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16

17

18 **Abstract**

19 Threats to nature becoming increasingly prominent, in order for biodiversity levels to persist,  
20 there is a critical need to improve implementation of conservation measures. In the oceans,  
21 the surveillance of fisheries is complex and inadequate, such that quantifying and locating  
22 non-declared and illegal fisheries is persistently problematic. Given that these activities  
23 dramatically impact oceanic ecosystems, through over-exploitation of fish stocks and bycatch  
24 of threatened species, innovative ways to monitor the oceans are urgently required. Here, we  
25 describe a new concept of ‘Ocean Sentinel’ using animals equipped with state-of-the-art  
26 loggers which monitor fisheries in remote areas. Albatrosses fitted with loggers detecting and  
27 locating the presence of vessels, and transmitting the information immediately to authorities,  
28 allowed the first estimation of the proportion of non-declared fishing vessels operating in  
29 National and International waters of Southern Ocean. We found that in international waters  
30 more than one third of vessels had no Automatic Identification System operating; in national  
31 Exclusive Economic Zones (EEZ) this proportion was lower on average, but variable  
32 according to EEZ. Ocean Sentinel was also able to provide unprecedented information on the  
33 attraction of seabirds to vessels, giving access to crucial information for risk assessment plans  
34 of threatened species. Attraction differed between species, age and vessels activity. Fishing  
35 vessels attracted more birds than other vessels and juveniles both encountering fewer vessels,  
36 and showed a lower attraction to vessels, than adults. This study shows that the development  
37 of new technologies offers the potential of implementing conservation policies by using wide-  
38 ranging seabirds to patrol oceans.

39

40

41 **Significance**

42 New technological approaches to improving remote surveillance of the oceans are necessary  
43 if we are to implement effective conservation. Of particular concern is locating non-declared  
44 and illegal fisheries that dramatically impact oceanic ecosystems. Here we demonstrate that  
45 new animal-borne satellite-relayed data loggers both detected and localised fishing vessels  
46 over large oceanic sectors. Attraction of albatrosses to fishing vessels differed according to  
47 species and age. We found high proportions of non-declared fishing vessels operating in  
48 international waters as well as in some remote national seas. Our results demonstrate the  
49 potential of using animals as Ocean Sentinels for operational conservation.

50

51 **INTRODUCTION**

52 The Anthropocene era is associated with increasing threats to nature and biodiversity (1), and  
53 as a result, conservation research is becoming increasingly sophisticated, in an attempt to  
54 protect ecosystems (2). Today conservation studies often focus on increasing the accuracy of  
55 information used to prioritise locations for conservation actions, e.g. delimitation of areas of  
56 conservation (3). Yet, it is increasingly recognised that the implementation of conservation  
57 measures is inadequate and a major hindrance in global conservation (4). There is a crucial  
58 need to improve the implementation of conservation research into practice and policy, beyond  
59 specific species or systems studied.

60 Compared to terrestrial habitats, the surveillance and implementation of conservation  
61 measures is considerably more complicated in marine systems. In particular international  
62 oceanic waters and remote areas are particularly challenging for political and logistical  
63 reasons. Fisheries are operating worldwide over National Economic Exclusive Zones (EEZs)  
64 and international waters. They have a profound effect on ecosystems through overexploitation  
65 of fish stocks, the removal of key ecosystem components and accidental capture of marine  
66 vertebrates (5). As a result, there is an urgent need for in depth reforms to fisheries  
67 management to improve fish abundance while increasing food security (6). Today basic  
68 knowledge about the distribution of fishing vessels is fundamental for the regulation of  
69 fishing activities, as well for the conservation of the oceans (7). Yet information about fishing  
70 vessel location is very difficult to obtain. It is eventually made available to authorities or  
71 international fisheries organisations through voluntary declaration using Vessel Monitoring  
72 Systems (VMS) or indirectly through the use of Automatic Identification Systems (AIS) (8).  
73 The former is generally used only in EEZs, the latter should be used both in EEZ and  
74 international waters to avoid collisions and may be accessed through dedicated sites  
75 ([www.marinetraffic.com](http://www.marinetraffic.com)). However, AIS are not used systematically, and can be switched off

76 from the vessel. In international waters, information on fishing effort and distribution may be  
77 completely lacking, or made available by Regional Fisheries Management Organisations  
78 (RFMO), such as tuna fisheries, but at a very coarse scale and in an aggregated form, making  
79 it impossible to have real time or regular (e.g. daily) information. Recent efforts have been  
80 made to improve this, through the use of AIS, allowing visualisation, tracking and sharing of  
81 data on global fishing activity (<https://globalfishingwatch.org>)(9, 10). However, this  
82 information is limited as it is complex to access in real time, and, furthermore, at any time  
83 AIS can be switched off, which is likely to be particular common by illegal fisheries. Yet  
84 information on the location of fishing vessels is critical since in many oceanic sectors non-  
85 declared and illegal fisheries are negatively affecting ecosystems through over exploitation  
86 and by catch of non-target species (11, 12). Among these species, bycatch of albatrosses and  
87 petrels is very high and these are among the most threatened bird species, with 100,000s  
88 killed by long line fisheries every year (13). Thus, there is a need to obtain better  
89 information on seabirds-fishery interactions (14).

90 Estimates of the overlap between seabirds and fisheries activities outside EEZ are at best  
91 available at large scale from RFMOs. It is in these international waters that information on  
92 seabird-fishery interactions are badly required to estimate global bycatch risks (15, 16). At  
93 present, risk assessments are based on the assumption that the co-occurrence of seabirds and  
94 fisheries in a large scale sector (generally 5° squares for tuna fisheries) leads to interactions,  
95 and therefore mortality risks. This has so far not been documented, and until today real degree  
96 of overlap can only be obtained by scaling down the analysis of interactions (17) by using  
97 high resolution VMS data and seabird tracking data. However VMS data do not exist in  
98 international waters and for most fisheries operating in EEZ VMS are rarely fully available to  
99 researchers, especially in real time. Obtaining real interaction information requires having fine  
100 scale information simultaneously on fisheries distribution and seabird movements, which is

101 rarely the case, generally restricted to limited EEZ areas (18). More importantly once  
102 interactions have been located, if an intervention from authority is required, there is a need for  
103 an immediate relay of information on these interactions.

104 Tracking of marine animals has been used widely to determine sites to protect (19), with the  
105 ultimate goal of improving conservation (20). In addition, during recent years, seabirds,  
106 marine mammals and turtles, fitted with a variety of loggers, have been used worldwide as  
107 oceanic samplers through equipment with bio-logging sensors (21, 22). These loggers have  
108 the potential to transmit information instantaneously through satellites, and make them  
109 available to agencies or researchers (23, 24). Recently a new logger detecting radar emissions  
110 of vessels has been developed, providing locations of interactions between albatrosses and  
111 vessels over vast oceanic sectors (25). Building on this new platform, we have developed a  
112 new concept of operational conservation based on new loggers that will allow the immediate  
113 transmission of vessel location for improving surveillance and enforcement.

114 By using wide-ranging large seabirds that are attracted to boats, such as albatrosses, petrels  
115 and gannets, we have developed the concept of OCEAN SENTINEL. Ocean Sentinels aim to  
116 provide more accurate information on the distribution of fisheries in any oceanic sector and to  
117 provide instantaneous information to authorities, international fisheries agreements or  
118 researchers, on the location of fishing boats. For the first large-scale test of the concept we  
119 have used albatrosses. Large albatrosses cover huge areas of the ocean surface (22 million  
120 square kilometres with 50 individuals equipped) and are highly attracted to fishing vessels  
121 which they can detect from up to 30 km away (26), making them particularly suitable  
122 patrollers of the oceans. The concept was tested between November 2018 and May 2019 in  
123 the Southern Indian Ocean, at Crozet, Kerguelen and Amsterdam Islands, where valuable and  
124 extensive fisheries operate, both in EEZs and in international oceanic waters. Its aim was to  
125 provide information on fisheries distribution in oceanic sectors where monitoring information

126 is currently not available. In the Southern Ocean, surveillance of the EEZs is extremely costly,  
127 and thus only occasional visits by Navy ships, provide monitoring for these zones.  
128 Furthermore, in international waters such surveillance is absent.

129 Here we present the first results of a six-month large-scale test of the Ocean Sentinel concept  
130 carried out in the south-western Indian Ocean. The specific aims of this paper are 1) to test  
131 whether it is possible to use animals as platforms to make research operational, especially for  
132 large scale surveillance, 2) to compare the efficiency of the concept to the other existing  
133 surveillance systems based on VMS, AIS satellite and naval ship-based surveillance, 3)  
134 provide for the first time an estimate of the proportion of vessels illegally deactivating their  
135 AIS system, by comparing the data made available by AIS system to those provided by the  
136 bird-borne radar detectors , 4) obtain more accurate information (occurrence and location) on  
137 interactions between fisheries and two threatened species, wandering and Amsterdam  
138 albatrosses, and test the assumption that co-occurrence of seabird and fisheries results in real  
139 interaction. We also provide a first estimate of the real proportion of birds attending fishing  
140 boat after co-occurrence, and how it differs between species and age classes.

141

## 142 **Material and methods**

143

### 144 **Loggers**

145 Since all boats at-sea use radars for safety and operational reasons, the ability to detect radar  
146 emissions from geolocating loggers provides accurate information on the location of boats.  
147 We have developed, with Sextant Technology, and tested between 2015 and 2017, a logger  
148 (XGPS) that provides the GPS location of the fitted animal and simultaneously detects radar



149 emissions (25). From this platform, we developed a new logger that includes this radar  
150 detector, a GPS antenna, a processor and memory, but with the additional of an Argos antenna  
151 for real time data transmission. It is powered by a lithium rechargeable battery which has a  
152 solar panel capable of recharging the device when on the bird. The GPS location can be  
153 programmed to record GPS fixes at intervals of 1sec to 1h. The Argos antenna sends this  
154 information at a programmable interval. Two models were developed: Centurion and XArgos.  
155 Centurion logger weights 65 g, measures 109 X 30 X 22 mm (see SI Appendix, fig. S1) and  
156 records all the information on-board but sends instantaneously through Argos the location of  
157 the radar detection as soon as a vessel is detected through its radar emission. Loggers were  
158 deployed on actively breeding birds, which alternate foraging trips at-sea with periods on the  
159 nest, making recovery simple. For our large scale field deployment test we programmed  
160 Centurions so that the GPS recorded fixes every 2 mins and the radar detector recorded the  
161 presence of radar emissions every 5 mins, for a duration of 1 min. If the logger received a  
162 radar signal, the radar information (location and number of radar detections) was sent in real  
163 time through the Argos system, and afterwards continuously during 12h. When no radar  
164 signals had been detected after 12h, data was stored on the device but not transmitted through  
165 Argos. The complete information, including GPS locations every 2 min and radar detections  
166 was then downloaded from the logger when the bird had returned to its nest. The logger must  
167 be recovered to download the entire information on the track of the bird.

168 XArgos loggers (55 g, 109 X 30 X 19 mm) record and send the location of the bird and the  
169 summary of the Radar Detector scanning (scan for radar emissions recorded during 1.5 mins  
170 every 15 mins) every hour through Argos. They were deployed on juveniles leaving the  
171 colony, where they remain at-sea for several years, without returning to land. In addition, they  
172 were deployed on immature birds, defined as birds that return to the colony for pair formation  
173 but have yet to commence breeding, post-breeding birds, which are either adult birds that

174 have successfully finished breeding or failed breeders, which are adult birds that have  
175 attempted to breed but failed to fledge a chick. All birds were captured on the colony but as  
176 no birds were actively breeding at deployment, the chance of logger recovery was very low,  
177 making these loggers optimal.

178

## 179 **Deployments**

180 A total of 169 individuals of wandering (*Diomedea exulans*) and Amsterdam (*Diomedea*  
181 *amsterdamensis*) albatrosses were equipped with Centurion (breeding adults) and XArgos  
182 loggers between November 2018 and March 2019 from Crozet, Kerguelen and Amsterdam  
183 (Table 1).

184 The loggers were attached to the back feathers using special tape (Tesa, Germany). For short-  
185 term deployment (Centurion loggers on breeding adults), the logger was removed after the  
186 bird returned on its nest after one foraging trip. For long-term deployment (XArgos loggers on  
187 juveniles, immature and post-breeding adults), the attachment was reinforced by Loctite glue  
188 on the contacts between the logger and the tape. XArgos detached from birds through the loss  
189 of feathers during moulting process after 3-6 months. The loggers represented 0.46% to  
190 0.93% of the bird body weight (wandering albatrosses weight between 7 and 12 kg,  
191 Amsterdam albatross between 6 and 10 kg), i.e. below the recommended maximum 3% of the  
192 bird's body mass for loggers attached (27).

193

## 194 **Vessel information and AIS data**

195 AIS data were made available through the Themis interface (CLS Toulouse) for the sector 20-  
196 70°S, 10-180°E. Through this system, all AIS emissions in the sector are recorded, and the

197 information was downloaded every day from the CLS server and stored in a database. During  
198 the study period, more than 100 million AIS locations were obtained. For each AIS location  
199 the following information was available: date, latitude, longitude, Ship Name, IMO number of  
200 the vessel (identity of International Marine Organisation), nationality, call sign, speed,  
201 heading, type of vessel (fishing, tanker, cargo, pleasure etc.), activity. The densities of AIS  
202 were highest along continents, and the distribution of AIS from fishing boats varied  
203 throughout the study period (Figure 1).

204

### 205 **Data access and accessibility**

206 The information sent by the Centurion/XArgos loggers are received by the Argos satellites,  
207 and made available within minutes through the Argos website. Every 10 minutes the data  
208 were automatically downloaded, treated and made available through a dedicated Web page of  
209 the Terres Australes Françaises National Reserve  
210 ([http://178.170.56.102/websig/lizmap/www/index.php/view/map/?  
211 repository=sentinel&project=ocean\\_sentinel](http://178.170.56.102/websig/lizmap/www/index.php/view/map/?repository=sentinel&project=ocean_sentinel)). Access to this site was given to the researchers,  
212 the TAAF Administration and to the Regional Operational Monitoring and Rescue Center  
213 based on Réunion Island (CROSS) which controls the movements of boats in the Western  
214 Indian Ocean. When a boat was detected by a bird the location appeared immediately on the  
215 interface (See SI Appendix, fig. S2).

216 During the study period, the Ocean Sentinel website was continuously consulted and regularly  
217 verified by the TAAF administration and the CROSS Control Centre. All detections of vessels  
218 were compared by the CROSS with the AIS data available, as well as with the VMS data  
219 from the fishery operating in the Crozet, Kerguelen and Amsterdam EEZ. Thus, the system

220 allowed an alert to any Navy Patrol vessels present in the EEZ for a control in case of a non-  
221 declared boat detected within the EEZ (Figure 2).

222

## 223 **Data Processing and Analyses**

224 All information received through Argos, were filtered based on Cyclic Redundancy Check  
225 (CRC) to remove improperly transmitted locations with failures. We then applied a speed  
226 filter of  $150 \text{ km.h}^{-1}$  to remove all implausible locations of bird movements. These data were  
227 then made available on the web site. Data downloaded from Centurion loggers after birds  
228 were recovered on the nest, were similarly filtered, and all data filtered were then stored in a  
229 database.

230 All bird data was then merged with AIS data so that to each bird location was associated to  
231 AIS information of any vessel occurring within 5 km (considered as the distance of a bird  
232 nearby boat and ATTENDING it, and corresponding to the range of radar detection for the  
233 logger –(25), and within 30 km (the maximum distance of detection of a boat by an albatross,  
234 considered as an ENCOUNTER (26)). To determine bird-boat distance and time spent  
235 ATTENDING and in ENCOUNTER we used the linearly interpolated AIS location the  
236 closest in time from the bird location. Birds attracted to fishing boats come close and stay for  
237 at least a couple of hours (28) so that we are confident that a series of consecutive boat  
238 locations recorded within proximity of a bird are not due to inaccurate spatio-temporal  
239 matching. All series (at least 2 successive) radar detections associated to GPS locations  
240 without gaps of more than 2 h were grouped into Radar Event. A Radar event was considered  
241 as an association with a boat.

242 Then the database was processed to associate to each bird location, each Radar Event,  
243 Attending (AIS within 5 km) and Encountering (AIS within 30 km) locations, the following  
244 parameters: bathymetry, international or EEZ waters and all information on the associated  
245 AIS boat (IMO number or identification number for the International Maritime Organisation,  
246 ship name, activity, nationality).

247 From the data base we calculated, for each individual bird, the number of vessels within 100  
248 km of each bird location, the number encountered (within 30 km) and the number attended  
249 (within 5 km or with a radar detection). From this we calculated first the proportion of  
250 vessels within 100km that were encountered and attended, and then from the number of  
251 vessels encountered, we estimated the proportion of these vessels were attended. We also  
252 calculated for all the encounters and attendance the proportion of all vessels that were fishing  
253 versus other types of vessels.

254 All data processing was performed under R environment. Statistical Analyses were  
255 performed under Statistica 12. Data will be made available through the online open access  
256 repository Figshare (<https://figshare.com>).

257

## 258 **RESULTS**

259

### 260 **Coverage of Ocean Sentinel**

261 Between the 1<sup>st</sup> of December 2018 and the 1st of June 2019, 632,333 GPS locations of  
262 albatrosses, together with 5108 Radar detections, were received from Argos or downloaded  
263 from centurion loggers. The 5108 radar detections, represented interactions with 353 different

264 boats, considered as boat events. Adult and immatures birds had a higher proportion of  
265 vessels than juveniles (Table 1). The simultaneous deployment of these loggers gave coverage  
266 of a wide area of more than 47 million km<sup>2</sup> (Fig. 3).

267 Radar detections were found throughout the albatrosses range (Fig. 3) but with high densities  
268 within the EEZs on the edge of the Kerguelen-Heard plateau (Fig. 4) and Crozet – Del Cano  
269 plateau (Fig. 3). Proportion of time spent in international waters varied according to bird  
270 breeding status ( $F_{3,133} = 5.1$ ,  $P=0.0049$ ) with juveniles and non-breeding adults spending more  
271 time in international waters than breeding adults and immatures (Table 1). The proportion of  
272 trips spent in the French EEZ differed between stages as well, adults spending more time in  
273 EEZ than juveniles ( $F_{3,133} = 5.8$ ,  $P=0.0024$ ) (Table 1).

274 For centurion loggers, fitted on breeding adults, the transmission of radar detection through  
275 Argos allowed access to the location of boats within 0.2 to 2h of the first contact between a  
276 bird and a vessel, and this information was accessible immediately through the Ocean  
277 Sentinel website.

278

## 279 **Comparison with AIS**

280 Among the 353 detections of vessels, 71.8% had a corresponding AIS signal, but 28.2% had  
281 no AIS signal within 30 km. The situation differed between EEZs and international waters. In  
282 EEZs 74.2% of radar events had a corresponding AIS signal within 30 km, i.e. 25.8% of boats  
283 detected in EEZ had no associated AIS identification. In international waters, this percentage  
284 increased to 36.9% (the difference between EEZ and international waters was significant:  
285 Fisher Exact test,  $P= 0.042$ ). The percentage of radar detection events without AIS differed  
286 between EEZs ( $\chi^2_{5} = 105.2$ ,  $P<0.001$ ) (Table 2).

288 For the French Crozet-Kerguelen EEZs, most of the radar detections with AIS corresponded  
289 to fishing vessels from the Réunion based French fishing fleet. For the Crozet and Kerguelen  
290 EEZ most of the radar detections events without AIS corresponded to the detections of  
291 surveillance ship from the French Navy (no AIS) and to the detection of declared fishing  
292 boats that had their AIS momentarily switched off but were recognised from their VMS  
293 position by CROSS. For the Amsterdam EEZ, half of radar detections were non-declared  
294 ships. On the border of EEZ several vessels were detected in operation, with AIS irregularly  
295 ON (e.g. Fig. 4). This was a Spanish vessel and several Chinese long-liner fishing at the edge  
296 of the Kerguelen and Crozet EEZs.

297 In international waters short encounters corresponded to encounters with vessels transiting in  
298 the range zone of albatrosses, with functioning AIS. This was particularly the case for  
299 transport ships in the high-density zone of vessels with AIS south east of South Africa (Fig.  
300 1). For long encounters with vessels (several hours of radar detections), half occurred with  
301 Asiatic long-liners, but half were not associated with an AIS signals, but occurred in the zone  
302 of high densities of Asiatic fishing boats operating, suggesting that within the fleets, a  
303 significant proportion of vessels had no AIS working.

304 77.4% of radar detection events occurred over shelves and shelf edges, with 99 events  
305 (28.1%) being not associated with an AIS within 5 km from the bird (Fig. 5). Over oceanic  
306 waters, 39.7% of events had no AIS. 28.2% of Radar Detection had no AIS information on  
307 the type of ship within 30 km (either no AIS at all or no AIS information on the ship type).  
308 83.3% of ships with radar detection and an AIS signal were fishing vessels, 11.1% Cargo or  
309 Tanker and 5.6% other vessels. Time spent attending fishing vessels was longer than for the  
310 other vessel types (4.8 h versus 2.4 h respectively;  $F_{2, 249} = 3.2$ ,  $P=0.045$ ).

311 In 403 events, where AIS were located within 5 km of birds, 188 (46.6%) had a radar  
312 detection with 132 (54.8% of events) for Centurion and 56 (35% of events) for XArgos.

313

### 314 **Co-occurrence and attraction**

315 Only 10% of individuals did not have any vessel within a range of 100 km during their trip.  
316 For those that had at least one vessel within 100km of their movement, 19.9%±20.4 came  
317 within 30 km of at least a vessel, and 6.3±11.9% attended a vessel. These values varied  
318 extensively according to the age of individuals with juveniles being less prone to encounter  
319 and approach vessels to attend it, than adults ( $F_{3,175}=5.8$ ,  $P<0.0001$  and  $F_{3,175}=7.7$ ,  $P<0.001$   
320 respectively) (Fig. 6a and b).

321 When birds encountered a vessel (within 30 km), 19.8±20.4% attended the vessel. Again, this  
322 value varied extensively according to the status, juveniles having a lower propensity to attend  
323 vessels encountered ( $F_{1,146}=8.2$ ,  $P<0.001$ ) (Fig. 6c).

324 Attractivity of vessels varied between species, with Amsterdam albatrosses being less  
325 attracted to vessels than wandering albatrosses (8.5±13.3% of Amsterdam albatrosses  
326 encountering a vessel approached at less than 5 km of the vessel compared to 21.1±22.8% for  
327 wanderings,  $F_{1,148}=4.4$ ,  $P=0.038$ ). Wandering albatrosses were also more likely to approach a  
328 fishing vessel if encountered, compared to other vessel type: 40.3% of encounters of fishing  
329 vessels resulted in an attendance, compared to 10.9% for other vessels ( $\chi^2_1= 81.2$ ,  $P<0.001$ ).

330

331

## 332 **DISCUSSION**



333 The ultimate goal of conservation research should be not only to provide ever-improving  
334 measures of priority areas to be protected, but to also provide new ways to improve of the  
335 implantation of recommendations to conserve biodiversity and sustainable resources of high  
336 importance to humans (3). In the oceans, among these processes, there is the need for new  
337 methods of surveillance of fisheries, and a way to better quantify and locate non-declared and  
338 illegal fisheries, particularly in international waters.

339 The first results of the Ocean Sentinel program indicate clearly that it is possible to use  
340 animals to improve our capacity for surveillance in very isolated oceanic sectors. They also  
341 allowed us to estimate the proportion of boats operating without AIS i.e. that were operating  
342 in EEZ and in international waters without the capacity to be located via standard monitoring  
343 systems. Finally, they provide accurate information on the interactions between two  
344 endangered species and fisheries, and differences existing between adults and young  
345 individuals.

346

### 347 **Capacity of improving prosecution**

348 Our study shows that it is possible to use bird-borne loggers to survey fishing activities over  
349 large oceanic sectors. The deployment of loggers on 169 individuals during a 6 month period  
350 gave a large coverage of the south-western Indian, extending through to New Zealand. The  
351 quasi-immediate transmission of more than 5000 radar detections through the Argos system to  
352 a web site, accessible to authorities, confirms that using large albatrosses as indicators of the  
353 presence of vessels is an efficient way to survey large areas where direct survey by patrolling  
354 vessels is rare and costly.

355 In the EEZs around Crozet and Kerguelen, where the French fishery targeting  
356 Patagonian tooth-fish operates, all vessels present were detected several times by breeding  
357 adults on the shelf's edges. In some cases, the declared vessels were detected by birds without  
358 associated AIS emissions: however, the identity of the vessel was confirmed by the CROSS  
359 through the VMS system. For this declared fishery, absence of AIS during radar detections  
360 was relatively rare. During the study period, no non-declared fishing vessel was detected in  
361 the EEZs of Crozet and Kerguelen, two in the EEZ around Amsterdam, and all detections in  
362 the EEZ around the Prince Edward Islands had no AIS. In addition, several vessels were  
363 detected with no AIS at the edges of the Kerguelen-Heard EEZ and of the Crozet and Prince  
364 Edward EEZ. For at least two cases, some boats had their AIS regularly switched off for long  
365 periods. In the EEZ around Crozet and Kerguelen the fishery is strictly controlled today by  
366 authorities using mitigation measure to reduce seabird mortality to very low numbers (29, 30).

367 In the CCAMLR zone and in international waters, at least half of the radar detections over  
368 several hours, corresponding to typical vessels in fishing operation, had no AIS associated.  
369 Most detections occurred in subtropical waters, where large Asiatic fisheries operate targeting  
370 tuna (31). Typically, the fleets are located through clusters of vessels with AIS but with  
371 irregular AIS transmissions and incomplete information on the identity of vessels. It is in  
372 these areas of tuna fisheries where AIS are often not transmitted that a significant number of  
373 radar detection occurred with no AIS (Fig. 5). Although the Indian Ocean Tuna Commission  
374 (IOTC) requires that fishing boats targeting tuna use at least two seabird mitigation methods  
375 selected from a range of methods (32), and that best practice to reduce mortality in these  
376 fisheries is well established (33), most tuna fisheries do not use mitigation measures apart for  
377 some countries which have adopted to use them voluntarily (31, 34, 35). Thus, it is in these  
378 waters that mortality risks in long-line fisheries are the highest and hence seabirds are at the  
379 highest risk.

380 The Ocean Sentinel (OS) concept appears offer a way forward to help develop new tools for  
381 surveillance and improved enforcement. First, OS provides researchers or international  
382 agreements for Fisheries Management (such as Tuna Commissions, IOTC, CCSBT etc.) or for  
383 Conservation (such as CCAMLR), unprecedented information on the distribution of fisheries  
384 in remote areas, where conventional methods are not available. We have shown that Ocean  
385 Sentinel was able to provide to national and regional authorities direct information about the  
386 presence of fishing boats in the region they manage. This is critical information for regions  
387 where surveillance by maritime or aerial patrols is not possible because of their remoteness  
388 and/or because of the extensive cost of surveillance. The Radar-Sat system ([www.asc-](http://www.asc-csa.gc.ca/fra/satellites/radarsat2)  
389 [csa.gc.ca/fra/satellites/radarsat2](http://www.asc-csa.gc.ca/fra/satellites/radarsat2)) can provide information on the potential presence of boats in  
390 a particular region through the detection of metallic masses. However, the cost for obtaining  
391 images is extremely high (for example 1.4M€/year for the TAAF area), and the information  
392 depends on the coverage by the satellite bands. More importantly, the detections provide only  
393 ‘potential’ signals of boat presence. Our preliminary examination shows that satellite images  
394 are available irregularly and when available, not all boats are detected by the system.

395 The only open access system providing information on fisheries is the Global Fishing Watch  
396 ([globalfishingwatch.org](http://globalfishingwatch.org)) that potentially enables anyone with an internet connection to see  
397 fishing activity anywhere in the ocean, with a two-day delay. The system is based on the  
398 detection of AIS signals sent by boats. We have shown that a significant proportion of vessels  
399 detected by our birds had no AIS. Since AIS can be switched off, and this probably occurs in  
400 illegal fisheries, full coverage of fishing activity using AIS is not possible. Ocean Sentinel  
401 appear to be a complementary tool for surveying fisheries in remote areas.

402 Apart from these two systems based on satellites, surveillance can be made by patrol boats or  
403 airplane, but the more remote the area, the more difficult and costly the surveillance. For  
404 example, in the Kerguelen and Crozet EEZs, airplane cannot be used, and Naval or

405 surveillance vessels are infrequently present in these remote areas. When present in the zone,  
406 they had access to Ocean Sentinel information. The CROSS used the Ocean Sentinel data to  
407 survey the zone indicating that the program has the potential to improve surveillance, and in  
408 case of the detection of illegal activities within EEZ, to improve enforcement efficiency.

409

## 410 **Co-occurrence, attraction and risk assessment**

411 Tracking of marine animals has been used extensively to delineate hot-spots of  
412 biodiversity (19, 36-38), with the ultimate goal of improving conservation through the setting  
413 of marine protected areas or the enforcement of conservation measures (20). In this context,  
414 overlapping seabird or turtle distribution with fisheries activities (when available, at various  
415 spatial scales) allows the estimation of interaction and estimate risks of bycatch (7, 39).  
416 However, this risk assessment is generally based on the strong assumption that the co-  
417 occurrence of seabirds and fisheries leads to interaction and mortality risks. This assumption  
418 may be correct when overlapping fine scale fishery activities but these are rarely available  
419 (28), especially in international waters where the information on fisheries distribution is at  
420 best available at large scales from RFMOs (15, 16). Based on the results of Ocean Sentinel,  
421 our study is the first to test the hypothesis that co co-occurrence at various scale leads to  
422 interaction. This hypothesis has been tested previously using vessels equipped with VMS in  
423 EEZ (14, 17, 26), whereas our study uses a system detecting not only vessels in EEZ, but also  
424 in international waters. Several seabird species, such as albatrosses, are well known to be  
425 attracted to fishing vessels. However, the attractivity of vessels to seabirds is difficult to study  
426 (14), and generally examined indirectly through the comparison of numbers of seabirds in co-  
427 occurrence with vessels at different spatial scales (40). Attraction of seabirds to fishing  
428 vessels is believed to be mainly the result of local, small scaled, co-occurrence (41). Our new

429 loggers have allowed us for the first time to estimate co-occurrence at various scales and  
430 attraction to vessels for two different species and different age classes. Juvenile individuals,  
431 during their first months at-sea, encountered fewer boats than adults or immature birds, and  
432 when co-occurring within 100km of a vessel had almost a zero probability of attending the  
433 vessel, whereas for adults 10% of birds attended such vessels. The low attendance rate of  
434 juvenile was the result of the low density of vessels in the range of juveniles, but also because  
435 juveniles were less attracted to vessels than adults. Amsterdam albatrosses forage in a sector  
436 with high boat densities, especially large tuna fisheries, compared to wandering albatrosses,  
437 yet the population is increasing with very low mortality rates at all ages (42, 43). Examination  
438 of encounter rates followed by attendance at the boat suggests that Amsterdam albatrosses  
439 attend fewer fishing boats compared to wandering albatrosses, despite encountering more  
440 boats. These results have strong implications for future risk assessment plans since it  
441 provides the first figure for the attraction of albatrosses to fishing boats and shows that  
442 attraction differs extensively between age classes and species.

443 Our data are also the first to indicate that adult albatrosses are more attracted to fishing  
444 vessels than to other type of boat. Short encounters at vessels in international waters generally  
445 correspond to birds crossing the route of large transport ships within the range of albatrosses.  
446 Birds never follow these boats for long periods (maximum two hours). Conversely, for fishing  
447 boats in operation, encounters are followed by long attendance periods. In the EEZ,  
448 attendance can last several hours on the shelf edge, corresponding to long-liners, targeting  
449 Patagonian tooth-fish (28).

450

## 451 **Conclusions**

452 The concept of Ocean Sentinel is flexible and can be applied to many other systems.  
453 According to the area and requests of local authorities, the accessibility of the data can be  
454 fully open-access through the web (for example in the case of international waters), or with  
455 limited access restricted to authorities through a password system (for example in EEZs where  
456 regulated fisheries operate). The system can be exploited in any situation where large seabirds  
457 attracted by boat (for example albatrosses are attracted by boat at distance of up to 30 km and  
458 cover millions of square kilometres during foraging trips) can be fitted with the Ocean  
459 Sentinel concept. Preliminary tests have been made with our loggers on other albatross  
460 populations in Hawaii and in the New Zealand region. The loggers can be deployed on  
461 smaller seabird size species such as gannets to detect fishing boats (44). However, our results  
462 show that the species and age class have to be selected carefully: in our case, adult wandering  
463 albatrosses appear to be excellent sentinel species, since they are very attracted by fishing  
464 vessels, and can detect them at 30 km distance. In addition, the system has the potential to  
465 provide unprecedented information on the attraction and attendance of seabirds to vessels,  
466 opening new perspectives for the study of behaviour of seabirds in relation to vessels, but also  
467 giving access to crucial information for risk assessment plans. The concept of Ocean Sentinel  
468 is complementary to other efforts aiming at providing independent information on fisheries  
469 distribution (9). It is a good example of how the development of new technologies applied to  
470 conservation make operational conservation possible, and could be used in other animal taxa  
471 such as sea turtle or sharks, where conservation actions and independent by-catch locations  
472 are critically required (45, 46).

473

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592

593

## Legends of figures

594

595 **Figure 1** - Distribution of AIS locations (for all vessels, left, and fishing vessels only, right) in  
596 the study sector – south Indian Ocean between Africa and New Zealand) recorded in January,  
597 February and March 2019. Number of vessels over 4 days randomly selected every week  
598 through each month, for squares of 125 km.

599

600 **Figure 2** - Schematisation of OCEAN SENTINEL concept: detection by Centurion loggers  
601 fitted on foraging albatross, immediate transmission by Argos system, analysis of data,  
602 provision of data on the TAAF/OCEAN SENTINEL website, comparison with VMS and AIS  
603 data, and alert in case of detection of undeclared activity, with potential control by Navy ship.

604

605 **Figure 3** – Southern Indian Ocean with the tracks of Crozet wandering albatrosses (green),  
606 Kerguelen wandering albatrosses (orange) and Amsterdam albatrosses (blue). Radar  
607 detections in yellow. EEZ limits in the yellow line.

608

609 **Figure 4** – Tracks of wandering albatrosses (as in Figure 3) and location of radar detections  
610 (yellow and black points) in the sector of the Kerguelen-Heard plateau. Star indicates location  
611 of the colony. EEZ limits in the yellow line.

612

613 **Figure 5 – a)** Study area showing the overall range (blue line, kernel 90% of all birds), core  
614 area (blue zone, kernel 50%) and the location of radar detection with AIS associated (green  
615 dots) and no AIS associated (red dots). Limit of EEZ in yellow. **b)** eastern part of the range.

616

617 **Figure 6 –** Average ( $\pm$  one S.E.) percentages of albatrosses of different age classes that (a)  
618 encountered (within 30 km from a vessel ) and (b) attended (within 5 km from a vessel) after  
619 being in a 100 km range from a vessel, and average percentage of albatrosses attending a  
620 vessel after encountering it.

621