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

Henri Weimerskirch[a,1], Julien Collet[a], Alexandre Corbeau[a], Adrien Pajot[a], Floran Hoarau[b], Cédric Marteau[b], Dominique Filippi[c], and Samantha C. Patrick[d]

[a]Centre d'Etudes Biologiques de Chizé CNRS, UMR 7372 CNRS–Université de la Rochelle, 79360 Villiers en Bois, France; [b]Direction de l'Environnement, Terres Australes et Antarctiques Françaises, 97410 Saint Pierre, La Réunion, France; [c]Sextant Technology, Ltd., Wellington 6012, New Zealand; and [d]School of Environmental Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom

Edited by Hugh P. Possingham, The Nature Conservancy, Sherwood, QLD, Australia, and approved December 28, 2019 (received for review September 9, 2019)

With threats to nature becoming increasingly prominent, in order for biodiversity levels to persist, there is a critical need to improve implementation of conservation measures. In the oceans, the surveillance of fisheries is complex and inadequate, such that quantifying and locating nondeclared and illegal fisheries is persistently problematic. Given that these activities dramatically impact oceanic ecosystems, through overexploitation of fish stocks and bycatch of threatened species, innovative ways to monitor the oceans are urgently required. Here, we describe a concept of "Ocean Sentinel" using animals equipped with state-of-the-art loggers which monitor fisheries in remote areas. Albatrosses fitted with loggers detecting and locating the presence of vessels and transmitting the information immediately to authorities allowed an estimation of the proportion of nondeclared fishing vessels operating in national and international waters of the Southern Ocean. We found that in international waters, more than one-third of vessels had no Automatic Identification System operating; in national Exclusive Economic Zones (EEZs), this proportion was lower on average, but variable according to EEZ. Ocean Sentinel was also able to provide unpreceded information on the attraction of seabirds to vessels, giving access to crucial information for risk-assessment plans of threatened species. Attraction differed between species, age, and vessel activity. Fishing vessels attracted more birds than other vessels, and juveniles both encountered fewer vessels and showed a lower attraction to vessels than adults. This study shows that the development of technologies offers the potential of implementing conservation policies by using wide-ranging seabirds to patrol oceans.

bio-logging | illegal fisheries | conservation | vessel attraction | seabird

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

Compared to terrestrial habitats, the surveillance and implementation of conservation measures is considerably more complicated in marine systems. In particular, international oceanic waters and remote areas are particularly challenging for political and logistical reasons. Fisheries are operating worldwide over National Economic Exclusive Zones (EEZs) and international waters. They have a profound effect on ecosystems through overexploitation of fish stocks, the removal of key ecosystem components, and accidental capture of marine vertebrates (5). As a result, there is an urgent need for in-depth reforms to fisheries management to improve fish abundance while increasing food security (6). Today, basic knowledge about the distribution of fishing vessels is fundamental for the regulation of fishing activities, as well for the conservation of the oceans (7). Yet, information about fishing-vessel location is very difficult to obtain. It is eventually made available to authorities or international fisheries organizations through voluntary declaration using Vessel Monitoring Systems (VMSs) or indirectly through the use of Automatic Identification Systems (AISs) (8). The former is generally used only in EEZs; the latter should be used both in EEZs and international waters to avoid collisions and may be accessed through dedicated sites (https://www.marinetraffic.com). However, AISs are not used systematically and can be switched off from the vessel. In international waters, information on fishing effort and distribution may be completely lacking or made available by Regional Fisheries Management Organizations (RFMOs), such as tuna fisheries, but at a very coarse scale and in an aggregated form, making it impossible to have real-time or regular (e.g., daily) information. Recent efforts have been made to improve this, through the use of AISs, allowing visualization, tracking, and sharing of data on global fishing activity (https://globalfishingwatch.org) (9, 10). However, this information is limited, as it is complex to access in real time, and, furthermore, at any time, AISs can be switched off, which is likely to be particular common by illegal fisheries. Yet,

Significance

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

Author contributions: H.W. designed research; H.W., J.C., and A.C. performed research; J.C., A.C., A.P., F.H., C.M., D.F., and S.C.P. contributed new reagents/analytic tools; H.W., J.C., A.C., and A.P. analyzed data; and H.W. and S.C.P. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Data deposition: Tracking database and Radar detection events have been deposited in the online open access repository Figshare (https://figshare.com/s/2481d8e6cf4aff484ffe).

[1]To whom correspondence may be addressed. Email: henriw@cebc.cnrs.fr.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1915499117/-/DCSupplemental.

First published January 27, 2020.

information on the location of fishing vessels is critical since in many oceanic sectors, nondeclared and illegal fisheries are negatively affecting ecosystems through overexploitation and by catch of nontarget species (11, 12). Among these species, bycatch of albatrosses and petrels is very high, and these are among the most threatened bird species, with hundreds of thousands killed by longline fisheries every year (13). Thus, there is a need to obtain better information on seabirds–fishery interactions (14).

Estimates of the overlap between seabirds and fisheries activities outside EEZ are, at best, available at a large scale from RFMOs. It is in these international waters that information on seabird–fishery interactions are badly needed to estimate global bycatch risks (15, 16). At present, risk assessments are based on the assumption that the co-occurrence of seabirds and fisheries in a large-scale sector (generally 5° squares for tuna fisheries) leads to interactions and, therefore, mortality risks. This has so far not been documented, and, until today, the real degree of overlap can only be obtained by scaling down the analysis of interactions (17) by using high-resolution VMS data and seabird tracking data. However, VMS data do not exist in international waters, and for most fisheries operating in EEZs, VMSs are rarely fully available to researchers, especially in real time. Obtaining real interaction information requires having fine-scale information simultaneously on fisheries distribution and seabird movements, which is rarely the case, generally restricted to limited EEZ areas (18). More importantly, once interactions have been located, if an intervention from authority is required, there is a need for an immediate relay of information on these interactions.

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

By using wide-ranging large seabirds that are attracted to boats, such as albatrosses, petrels, and gannets, we have developed the concept of an Ocean Sentinel (OS). OSs aim to provide more accurate information on the distribution of fisheries in any oceanic sector and to provide instantaneous information to authorities, international fisheries agreements, or researchers on the location of fishing boats. For a large-scale test of the concept, we have used albatrosses. Large albatrosses cover huge areas of the ocean surface (22 million km^2 with 50 individuals equipped) and are highly attracted to fishing vessels, which they can detect from up to 30 km away (26), making them particularly suitable patrollers of the oceans. The concept was tested between November 2018 and May 2019 in the Southern Indian Ocean, at Crozet, Kerguelen, and Amsterdam Islands, where valuable and extensive fisheries operate, both in EEZs and in international oceanic waters. Its aim was to provide information on fisheries distribution in oceanic sectors where monitoring information is currently not available. In the Southern Ocean, surveillance of the EEZs is extremely costly, and, thus, only occasional visits by Navy ships provide monitoring for these zones. Furthermore, in international waters, such surveillance is absent.

Here, we present the first results of a 6-mo large-scale test of the OS concept carried out in the southwestern Indian Ocean. The specific aims of this paper are 1) to test whether it is possible to use animals as platforms to make research operational, especially for large-scale surveillance; 2) to compare the efficiency of the concept to the other existing surveillance systems based on VMS, AIS satellite, and naval ship-based surveillance; 3) provide an estimate of the proportion of vessels illegally deactivating their AIS, by comparing the data made available by AIS to those provided by the bird-borne radar detectors; and 4) obtain more accurate information (occurrence and location) on interactions between fisheries and two threatened species, wandering and Amsterdam albatrosses, and test the assumption that co-occurrence of seabird and fisheries results in real interaction. We also provide an estimate of the real proportion of birds attending fishing boats after co-occurrence and how it differs between species and age classes.

Material and Methods

Loggers. Since all boats at sea use radar for safety and operational reasons, the ability to detect radar emissions from geolocating loggers provides accurate information on the location of boats. We have developed, with Sextant Technology, and tested between 2015 and 2017, a logger (XGPS) that provides the global positioning system (GPS) location of the fitted animal and simultaneously detects radar emissions (25). From this platform, we developed a logger that includes this radar detector, a GPS antenna, a processor, and memory, but with the addition of an Argos antenna for real-time data transmission. It is powered by a lithium rechargeable battery, which has a solar panel capable of recharging the device when on the bird. The GPS location can be programmed to record GPS fixes at intervals of 1 s to 1 h. The Argos antenna sends this information at a programmable interval. Two models were developed: Centurion and XArgos.

The Centurion logger weighs 65 g, measures 109 × 30 × 22 mm (*SI Appendix*, Fig. S1), and records all of the information on board but sends instantaneously through Argos the location of the radar detection as soon as a vessel is detected through its radar emission. Loggers were deployed on actively breeding birds, which alternate foraging trips at sea with periods on the nest, making recovery simple. For our large-scale field-deployment test, we programmed Centurions so that the GPS recorded fixes every 2 min and the radar detector recorded the presence of radar emissions every 5 min, for a duration of 1 min. If the logger received a radar signal, the radar information (location and number of radar detections) was sent in real time through the Argos system and afterward continuously during 12 h. When no radar signals had been detected after 12 h, data were stored on the device but not transmitted through Argos. The complete information, including GPS locations every 2 min and radar detections, was then downloaded from the logger when the bird had returned to its nest. The logger must be recovered to download the entire information on the track of the bird.

XArgos loggers (55 g, 109 × 30 × 19 mm) recorded and sent the location of the bird and the summary of the radar detector scanning (scan for radar emissions recorded during 1.5 min every 15 min) every hour through Argos. They were deployed on juveniles leaving the colony, where they remained at sea for several years, without returning to land. In addition, they were deployed on immature birds, defined as birds that return to the colony for pair formation but have yet to commence breeding; postbreeding birds, which are adult birds that have successfully finished breeding; or failed breeders, which are adult birds that have attempted to breed but failed to fledge a chick. All birds were captured on the colony, but as no birds were actively breeding at deployment, the chance of logger recovery was very low, making these loggers optimal.

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

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

ENVIRONMENTAL SCIENCES

Table 1. Numbers of individual birds equipped with Centurion loggers at Crozet, Kerguelen, and Amsterdam and percentage of time spent in international waters and in the French EEZ around Crozet, Kerguelen, and Amsterdam

	Number of birds equipped with Centurion loggers*				% time in international waters	% in French EEZ
	Crozet	Kerguelen	Amsterdam	Total		
Juveniles (XArgos)	16 (11, 8.3%)	23 (18, 27.7%)	10 (8, 37.5%)	49 (38, 23.7%)	61.7 ± 21.0	30.8 ± 23.7
Breeding adults (Centurion) – number of deployments	50 (45, 63.3%)	30 (24, 75.9%)	10 (8, 40%)	90 (77, 64.7%)	40.1 ± 35.2	55.1 ± 37.1
Postbreeding adults (XArgos)	8 (6, 70%)	2 (2, 0%)		10 (8, 53.8%)	61.7 ± 33.4	28.6 ± 33.8
Immature (XArgos)	12 (12, 81.8%)	8 (8, 50%)		20 (20, 68.4%)	33.5 ± 38.5	62.2 ± 41.0

*Number with enough location and percentage of individuals with radar detection are in parentheses.

Vessel Information and AIS Data. AIS data were made available through the Themis interface (Collecte Localisation Satellites [CLS] Toulouse) for the sector 20 to 70°S, 10 to 180°E. Through this system, all AIS emissions in the sector were recorded, and the information was downloaded every day from the CLS server and stored in a database. During the study period, more than 100 million AIS locations were obtained. For each AIS location, the following information was available: date, latitude, longitude, ship name, identity of International Marine Organization (IMO) number of the vessel, nationality, call sign, speed, heading, type of vessel (fishing, tanker, cargo, pleasure, etc.), and activity. The densities of AIS were highest along continents, and the distribution of AIS from fishing boats varied throughout the study period (Fig. 1).

Data Access and Accessibility. The information sent by the Centurion/XArgos loggers were received by the Argos satellites and made available within minutes through the Argos website. Every 10 min, the data were automatically downloaded, treated, and made available through a dedicated web page of the Terres Australes Françaises National Reserve. Access to this site was given to the researchers, the Terres Australes et Antarctiques Françaises (TAAF) administration, and to Regional Operational Monitoring and Rescue Center based on Réunion Island (CROSS), which controls the movements of boats in the Western Indian Ocean. When a boat was detected by a bird, the location appeared immediately on the interface (*SI Appendix*, Fig. S2).

During the study period, the OS website was continuously consulted and regularly verified by the TAAF administration and the CROSS Control Centre. All detections of vessels were compared by the CROSS with the AIS data available, as well as with the VMS data from the fishery operating in the Crozet, Kerguelen, and Amsterdam EEZs. Thus, the system allowed an alert to any Navy patrol vessels present in the EEZ for a control in case of a non-declared boat detected within the EEZ (Fig. 2).

Data Processing and Analyses. All information received through Argos was filtered based on a cyclic redundancy check to remove improperly transmitted locations with failures. We then applied a speed filter of 150 $km \cdot h^{-1}$ to remove all implausible locations of bird movements. These data were then made available on the website. Data downloaded from Centurion loggers after birds were recovered on the nest were similarly filtered, and all data filtered were then stored in a database.

All bird data were then merged with AIS data so that to each bird location was associated to AIS information of any vessel occurring within 5 km [considered as the distance of a bird nearby boat and attending it, and corresponding to the range of radar detection for the logger (25)] and within 30 km [the maximum distance of detection of a boat by an albatross, considered as an encounter (26)]. To determine bird–boat distance and time spent attending and in encounter, we used the linearly interpolated AIS location the closest in time from the bird location. Birds attracted to fishing boats come close and stay for at least a couple of hours (28), so that we are confident that a series of consecutive boat locations recorded within proximity of a bird are not due to inaccurate spatiotemporal matching. All series (at least two successive) radar detections associated to GPS locations without gaps of more than 2 h were grouped into a radar event. A radar event was considered as an association with a boat.

Then, the database was processed to associate to each bird location, each radar event, attending (AIS within 5 km), and encountering (AIS within 30 km) locations the following parameters: bathymetry, international or EEZ waters, and all information on the associated AIS boat (IMO number or, ship name, activity, and nationality).

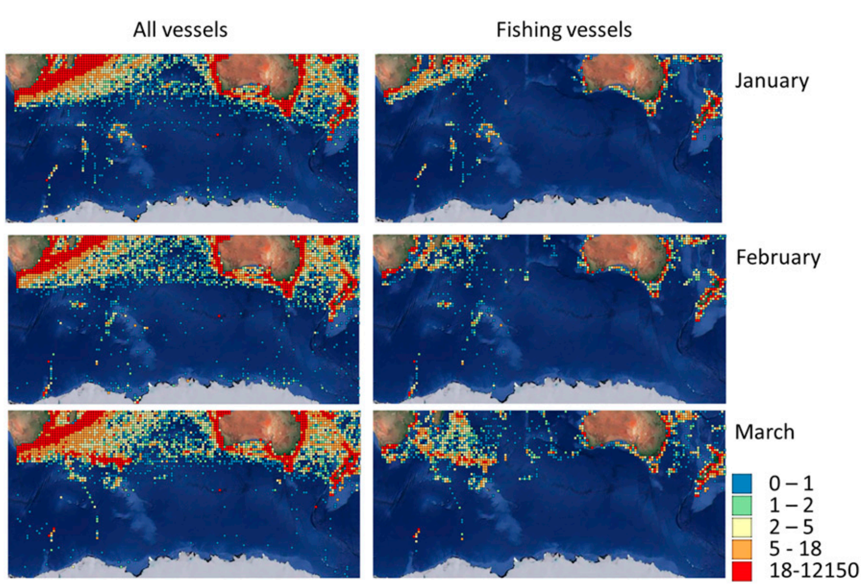

Fig. 1. Distribution of AIS locations (for all vessels [*Left*] and fishing vessels only [*Right*]) in the study sector (south Indian Ocean between Africa and New Zealand) recorded in January, February, and March 2019. Shown is the number of vessels over 4 d randomly selected every week through each month, for squares of 125 km.

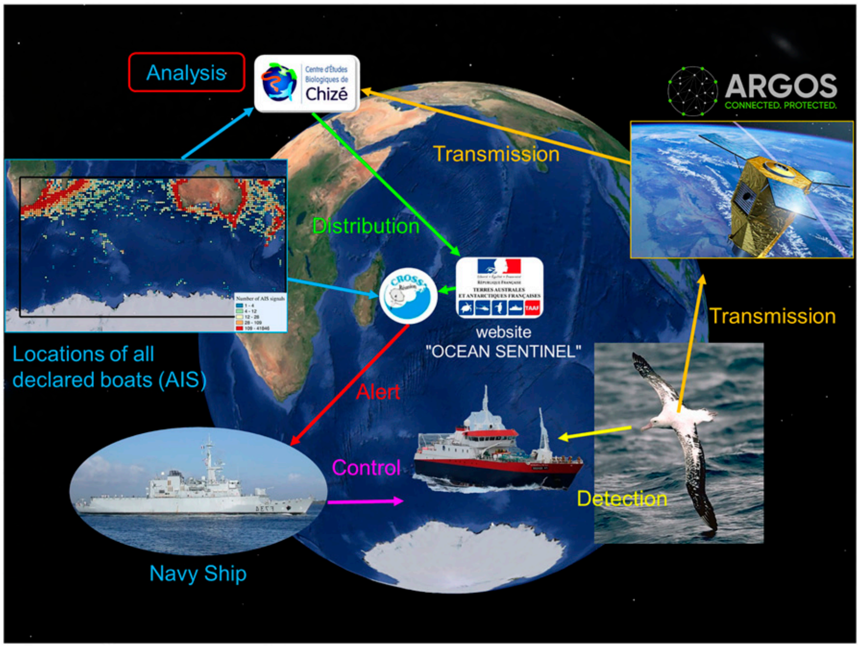

Fig. 2. Schematization of OS concept: detection by Centurion loggers fitted on foraging albatross, immediate transmission by Argos system, analysis of data, provision of data on the TAAF/OS website, comparison with VMS and AIS data, and alert in case of detection of undeclared activity, with potential control by Navy ship.

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

All data processing was performed under the R environment. Statistical analyses were performed under Statistica (Version 12). Data have been made available through the online open-access repository Figshare (https://figshare.com/s/2481d8e6cf4aff484ffe) (29).

Results

Coverage of OSs. Between the first of December 2018 and the first of June 2019, a total of 632,333 GPS locations of albatrosses, together with 5,108 radar detections, were received from Argos or downloaded from Centurion loggers. The 5,108 radar detections represented interactions with 353 different boats, considered as boat events. Adult and immature birds had a higher proportion of vessels than juveniles (Table 1). The simultaneous deployment of these loggers gave coverage of a wide area of more than 47 million km^2 (Fig. 3).

Radar detections were found throughout the albatrosses' range (Fig. 3), but with high densities within the EEZs on the edge of the Kerguelen–Heard plateau (Fig. 4) and Crozet–Del Cano plateau (Fig. 3). Proportion of time spent in international waters varied according to bird breeding status ($F_{3,133} = 5.1$, $P = 0.0049$), with juveniles and nonbreeding adults spending more time in international waters than breeding adults and immatures (Table 1). The proportion of trips spent in the French EEZ

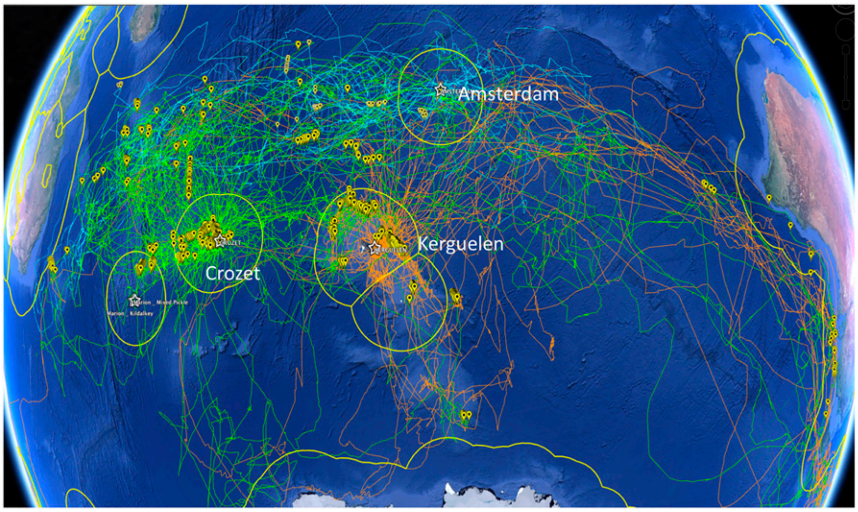

Fig. 3. Southern Indian Ocean with the tracks of Crozet wandering albatrosses (green), Kerguelen wandering albatrosses (orange), and Amsterdam albatrosses (blue). Radar detections are in yellow. EEZ limits are in the yellow line.

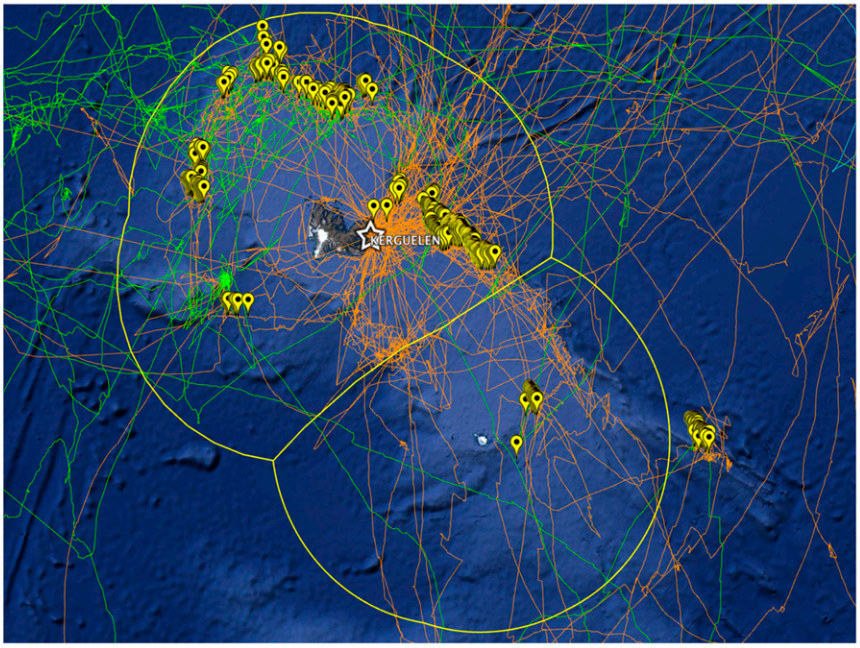

Fig. 4. Tracks of wandering albatrosses (as in Fig. 3) and location of radar detections (yellow and black points) in the sector of the Kerguelen–Heard plateau. Star indicates location of the colony. EEZ limits are in the yellow line.

differed between stages as well, with adults spending more time in the EEZ than juveniles ($F_{3,133}$ = 5.8, P = 0.0024) (Table 1).

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

Comparison with AIS. Among the 353 detections of vessels, 71.8% had a corresponding AIS signal, but 28.2% had no AIS signal within 30 km. The situation differed between EEZs and international waters. In EEZs, 74.2% of radar events had a corresponding AIS signal within 30 km; i.e., 25.8% of boats detected in EEZ had no associated AIS identification. In international waters, this percentage increased to 36.9% (the difference between EEZ and international waters was significant; Fisher exact test, P = 0.042). The percentage of radar-detection events without AIS differed between EEZs (χ^2_5 = 105.2, P < 0.001) (Table 2).

For the French Crozet–Kerguelen EEZs, most of the radar detections with AIS corresponded to fishing vessels from the Réunion-based French fishing fleet. For the Crozet and Kerguelen EEZ, most of the radar detection events without AIS corresponded to the detections of surveillance ship from the French Navy (no AIS) and to the detection of declared fishing boats that had their AIS momentarily switched off but were recognized from their VMS position by CROSS. For the Amsterdam EEZ, half of the radar detections were nondeclared ships. On the border of the EEZ, several vessels were detected in operation, with AIS irregularly on (e.g., Fig. 4). This was a Spanish vessel and several Chinese long-liners fishing at the edge of the Kerguelen and Crozet EEZs.

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

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

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

Table 2. Percentage of time (average ± SD) spent in international waters and in EEZs and a number of radar detection and proportion of detection with no AIS associated

EEZ	Average % time spent in EEZ	Number of radar-detection events within EEZ	% with no AIS
International	42.2 ± 35.9	78	36.9
Crozet	30.5 ± 40.4	93	14.6
Kerguelen	18.5 ± 32.4	125	14.9
Amsterdam	3.4 ± 12.9	6	50
Heard	1.8 ± 7.9	4	0
Prince Edward	1.4 ± 7.3	31	100
Australia	1.3 ± 5.2	11	18.2
New Zealand	0.3 ± 2.6	5	20.0
Antarctica	0.3 ± 2.4	0	
South Africa	0.03 ± 0.3	0	

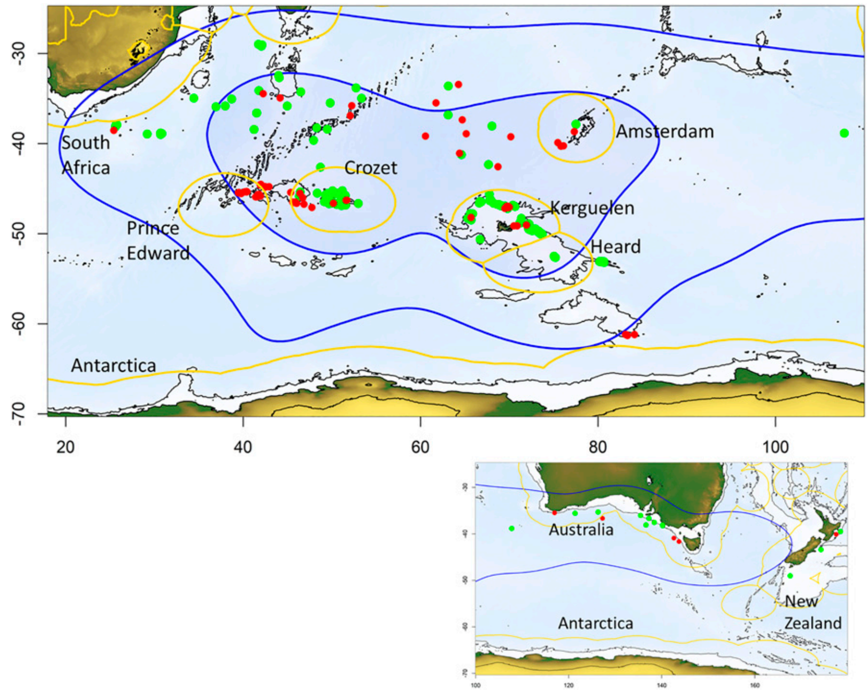

Fig. 5. (*Upper*) Study area showing the overall range (blue line; kernel 90% of all birds), core area (blue zone; kernel 50%), and the location of radar detection with AIS associated (green dots) and no AIS associated (red dots). Limit of EEZ is in yellow. (*Lower*) Eastern part of the range.

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

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

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

Discussion

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

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

Capacity of Improving Prosecution. Our study shows that it is possible to use bird-borne loggers to survey fishing activities over large oceanic sectors. The deployment of loggers on 169 individuals during a 6-mo period gave a large coverage of the southwestern Indian Ocean, extending through to New Zealand. The quasiimmediate transmission of more than 5,000 radar detections through the Argos system to a website, accessible to authorities, confirmed that using large albatrosses as indicators of the presence of vessels is an efficient way to survey large areas where direct survey by patrolling vessels is rare and costly.

In the EEZs around Crozet and Kerguelen, where the French fishery targeting Patagonian toothfish operates, all vessels present were detected several times by breeding adults on the shelf's edges. In some cases, the declared vessels were detected by birds without associated AIS emissions: However, the identity of the vessel was confirmed by the CROSS through the VMS system. For this declared fishery, absence of AIS during radar detections was relatively rare. During the study period, no nondeclared fishing vessel was detected in the EEZs of Crozet and Kerguelen, two were detected in the EEZ around Amsterdam, and all detections in the EEZ around the Prince Edward Islands had no AIS. In addition, several vessels were detected with no AIS at the edges of the Kerguelen–Heard EEZ and of the Crozet and Prince Edward EEZ. For at least two cases, some boats had their AIS regularly switched off for long periods. In the EEZ around Crozet and Kerguelen, the fishery is strictly controlled today by authorities using mitigation measure to reduce seabird mortality to very low numbers (30, 31).

In the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) zone and in international waters, at least half of the radar detections over several hours, corresponding

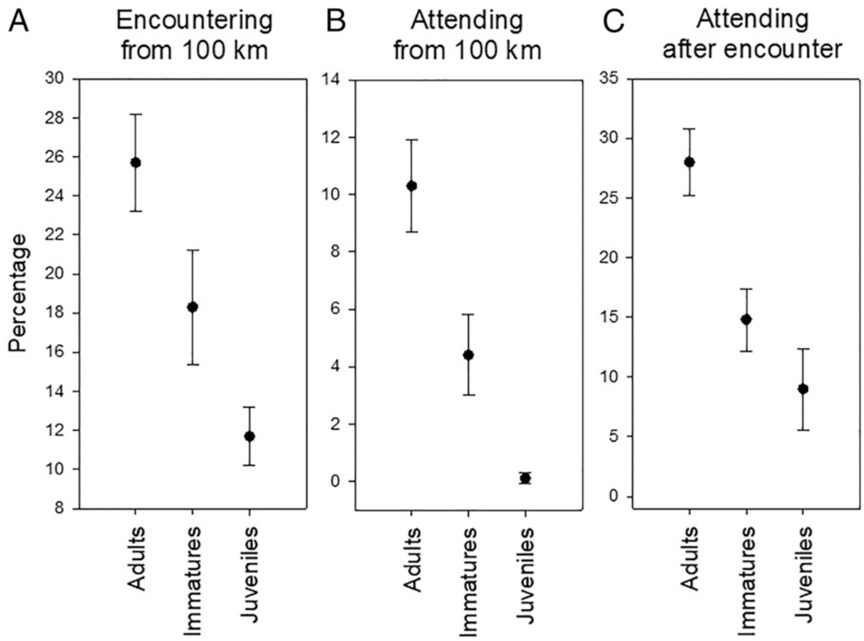

Fig. 6. Average (±SE) percentages of albatrosses of different age classes that encountered (within 30 km from a vessel) (*A*) and attended (within 5 km from a vessel) after being in a 100-km range from a vessel (*B*) and average percentage of albatrosses attending a vessel after encountering it (*C*).

to typical vessels in fishing operation, had no AIS associated. Most detections occurred in subtropical waters, where large Asiatic fisheries operate targeting tuna (32). Typically, the fleets are located through clusters of vessels with AIS, but with irregular AIS transmissions and incomplete information on the identity of vessels. It is in these areas of tuna fisheries where AISs are often not transmitted that a significant number of radar detection occurred with no AIS (Fig. 5). Although the Indian Ocean Tuna Commission (IOTC) requires that fishing boats targeting tuna use at least two seabird-mitigation methods selected from a range of methods (33), and that best practice to reduce mortality in these fisheries is well established (34), most tuna fisheries do not use mitigation measures, apart from some countries which have adopted to use them voluntarily (15, 32, 35). Thus, it is in these waters that mortality risks in long-line fisheries are the highest, and, hence, seabirds are at the highest risk.

The OS concept appears offer a way forward to help develop tools for surveillance and improved enforcement. First, OS provides researchers or international agreements for fisheries management (such as Tuna Commissions, IOTC, the Commission for the Conservation of Southern Bluefin Tuna, etc.) or for conservation (such as CCAMLR) unprecedented information on the distribution of fisheries in remote areas, where conventional methods are not available. We have shown that OS was able to provide to national and regional authorities direct information about the presence of fishing boats in the region they manage. This is critical information for regions where surveillance by maritime or aerial patrols is not possible because of their remoteness and/or because of the extensive cost of surveillance. The Radar-Sat system (https://www.asc-csa.gc.ca/fra/satellites/radarsat2/) can provide information on the potential presence of boats in a particular region through the detection of metallic masses. However, the cost for obtaining images is extremely high (for example, 1.4M€/y for the TAAF area), and the information depends on the coverage by the satellite bands. More importantly, the detections provide only "potential" signals of boat presence. Our preliminary examination shows that satellite images are available irregularly, and, when available, not all boats are detected by the system.

The only open-access system providing information on fisheries is the Global Fishing Watch (https://globalfishingwatch.org/) that potentially enables anyone with an internet connection to see fishing activity anywhere in the ocean, with a 2-d delay. The system is based on the detection of AIS signals sent by boats. We have shown that a significant proportion of vessels detected by our birds had no AIS. Since AIS can be switched off, and this probably occurs in illegal fisheries, full coverage of fishing activity using AIS is not possible. OSs appear to be a complementary tool for surveying fisheries in remote areas.

Apart from these two systems based on satellites, surveillance can be made by patrol boats or airplane, but the more remote the area, the more difficult and costly the surveillance. For example, in the Kerguelen and Crozet EEZs, airplanes cannot be used, and naval or surveillance vessels are infrequently present in these remote areas. When present in the zone, they had access to OS information. The CROSS used the OS data to survey the zone, indicating that the program has the potential to improve surveillance, and in case of the detection of illegal activities within EEZ, to improve enforcement efficiency.

Co-Occurrence, Attraction, and Risk Assessment. Tracking of marine animals has been used extensively to delineate hot spots of biodiversity (19, 36–38), with the ultimate goal of improving conservation through the setting of marine protected areas or the enforcement of conservation measures (20). In this context, overlapping seabird or turtle distribution with fisheries activities (when available, at various spatial scales) allows the estimation of interaction and estimate risks of bycatch (7, 39). However, this risk assessment is generally based on the strong assumption that the co-occurrence of seabirds and fisheries leads to interaction and mortality risks. This assumption may be correct when overlapping fine-scale fishery activities, but these are rarely available (28), especially in international waters, where the information on fisheries distribution is at best available at large scales from RFMOs (15, 16). Based on the results of OS, our study tests the hypothesis that co-occurrence at various scales leads to interaction. This hypothesis has been tested by using vessels equipped with VMS in EEZs (14, 17, 26), whereas our study used a system detecting not only vessels in EEZs, but also in international waters. Several seabird species, such as albatrosses, are well known to be attracted to fishing vessels. However, the attractivity of vessels to seabirds is difficult to study (14) and is generally examined indirectly through the comparison of numbers of seabirds in co-occurrence with vessels at different spatial scales (40). Attraction of seabirds to fishing vessels is believed to be mainly the result of local, small-scaled co-occurrence (41). Our loggers have allowed us to estimate co-occurrence at various scales and attraction to vessels for two different species and different age classes. Juvenile individuals, during their first months at sea, encountered fewer boats than adults or immature birds, and when co-occurring within 100 km of a vessel had almost a zero probability of attending the vessel, whereas for adults, 10% of birds attended such vessels. The low attendance rate of juvenile was the result of the low density of vessels in the range of juveniles, but also because juveniles were less attracted to vessels than adults. Amsterdam albatrosses forage in a sector with high boat densities, especially large tuna fisheries, compared to wandering albatrosses, yet the population is increasing with very low mortality rates at all ages (42, 43). Examination of encounter rates followed by attendance at the boat suggests that Amsterdam albatrosses attend fewer fishing boats compared to wandering albatrosses, despite encountering more boats. These results have strong implications for future risk-assessment plans since they provide a figure for the attraction of albatrosses to fishing boats and show that attraction differs extensively between age classes and species.

Our data also indicate that adult albatrosses are more attracted to fishing vessels than to other types of boats. Short encounters at vessels in international waters generally correspond to birds crossing the route of large transport ships within the range of albatrosses. Birds never follow these boats for long periods (maximum 2 h). Conversely, for fishing boats in operation, encounters are followed by long attendance periods. In the EEZ, attendance can last several hours on the shelf edge, corresponding to long-liners, targeting Patagonian toothfish (28).

Conclusions

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

ACKNOWLEDGMENTS. The study is a contribution to the Program EARLYLIFE funded by a European Research Council (ERC) Advanced Grant under the European Community's Seven Framework Program FP7/2007–2013 (Grant Agreement ERC-2012-ADG_20120314 [to H.W.) and to the Program OS funded by the ERC under European Community's H2020 Program (Grant Agreement ERC-2017-PoC_780058 [to H.W.]). The fieldwork was also funded by Institut Polaire Français Paul-Émile Victor Program 109 and was only possible thanks to the help of fieldworkers, especially Jeremy Dechartre, Aude Schreiber, Tobie Getti, Yuseke Goto, Yoshi Yonehara, and Florent Lacoste. The field procedures and manipulations on Crozet, Kerguelen, and Amsterdam were given permission by the Préfet of Terres Australes et Antarctiques Françaises. We thank the Reserve Nationale des TAAF for help with the development of the website and for funding loggers deployed on Amsterdam Island and Florient Orgeret for comments on the manuscript.

ENVIRONMENTAL SCIENCES

1. P. J. Crutzen, E. F. Stoermer, The Anthropocene. *Global Change Newsl.* **41**, 17–18 (2000).
2. R. T. Corlett, The Anthropocene concept in ecology and conservation. *Trends Ecol. Evol.* **30**, 36–41 (2015).
3. A. T. Knight, R. M. Cowling, B. M. Campbell, An operational model for implementing conservation action. *Conserv. Biol.* **20**, 408–419 (2006).
4. N. Salafsky, R. Margoluis, K. H. Redford, J. G. Robinson, Improving the practice of conservation: A conceptual framework and research agenda for conservation science. *Conserv. Biol.* **16**, 1469–1479 (2002).
5. D. Pauly, R. Watson, J. Alder, Global trends in world fisheries: Impacts on marine ecosystems and food security. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **360**, 5–12 (2005).
6. C. Costello *et al*., Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 5125–5129 (2016).
7. R. L. Lewison, L. B. Crowder, A. J. Read, S. A. Freeman, Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol. Evol.* **19**, 598–604 (2004).
8. D. A. Kroodsma *et al*., Tracking the global footprint of fisheries. *Science* **359**, 904–908 (2018).
9. W. Merten *et al*., Global Fishing Watch: Bringing transparency to global commercial fisheries. arXiv:1609.08756 (28 September 2016).
10. D. C. Dunn *et al*., Empowering high seas governance with satellite vessel tracking data. *Fish Fish.* **19**, 729–739 (2018).
11. D. Pauly *et al*., Towards sustainability in world fisheries. *Nature* **418**, 689–695 (2002).
12. D. Grémillet *et al*., Persisting worldwide seabird-fishery competition despite seabird community decline. *Curr. Biol.* **28**, 4009–4013.e2 (2018).
13. J. P. Croxall *et al*., Seabird conservation status, threats and priority actions: A global assessment. *Bird Conserv. Int.* **22**, 1–34 (2012).
14. T. W. Bodey *et al*., Seabird movement reveals the ecological footprint of fishing vessels. *Curr. Biol.* **24**, R514–R515 (2014).
15. G. N. Tuck *et al*., An assessment of seabird-fishery interactions in the Atlantic Ocean. *ICES J. Mar. Sci.* **68**, 1628–1637 (2011).
16. T. A. Clay *et al*., A comprehensive assessment of fisheries bycatch risk for threatened seabird populations. *J. Appl. Ecol.* **56**, 1882–1893 (2019).
17. L. G. Torres, P. M. Sagar, D. R. Thompson, R. A. Phillips, Scaling down the analysis of seabird-fishery interactions. *Mar. Ecol. Prog. Ser.* **473**, 275–289 (2013).
18. J. Croxall *et al*., Appropriate scales and data to manage seabird-fishery interactions: Comment on Torres et al.(2013). *Mar. Ecol. Prog. Ser.* **493**, 297–300 (2013).
19. B. G. Lascelles, G. M. Langham, R. A. Ronconi, J. B. Reid, From hotspots to site protection: Identifying Marine Protected Areas for seabirds around the globe. *Biol. Conserv.* **156**, 5–14 (2012).
20. G. C. Hays *et al*., Translating marine animal tracking data into conservation policy and management. *Trends Ecol. Evol.* **34**, 459–473 (2019).
21. C. C. Wilmers *et al*., The golden age of bio-logging: How animal-borne sensors are advancing the frontiers of ecology. *Ecology* **96**, 1741–1753 (2015).
22. N. E. Hussey *et al*., ECOLOGY. Aquatic animal telemetry: A panoramic window into the underwater world. *Science* **348**, 1255642 (2015).
23. R. Harcourt *et al*., Animal-borne telemetry: An integral component of the ocean observing toolkit. *Front. Mar. Sci.* **6**, 326 (2019).
24. J.-B. Charrassin *et al*., Southern Ocean frontal structure and sea-ice formation rates revealed by elephant seals. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 11634–11639 (2008).
25. H. Weimerskirch, D. P. Filippi, J. Collet, S. M. Waugh, S. C. Patrick, Use of radar detectors to track attendance of albatrosses at fishing vessels. *Conserv. Biol.* **32**, 240–245 (2018).
26. J. Collet, S. C. Patrick, H. Weimerskirch, Albatrosses redirect flight towards vessels at the limit of their visual range. *Mar. Ecol. Prog. Ser.* **526**, 199–205 (2015).
27. R. A. Phillips, J. C. Xavier, J. P. Croxall, Effects of satellite transmitters on albatrosses and petrels. *Auk* **120**, 1082–1090 (2003).
28. J. Collet, S. C. Patrick, H. Weimerskirch, Behavioral responses to encounter of fishing boats in wandering albatrosses. *Ecol. Evol.* **7**, 3335–3347 (2017).
29. H. Weimerskirch *et al*., Data_OCEAN_SENTINEL_Weimerskirch_et_al_2018_2019. Figshare. https://figshare.com/articles/Data_OCEAN_SENTINEL_Weimerskirch_et_al_2018_2019/10289096. Deposited 13 November 2019.
30. K. Delord, N. Gasco, H. Weimerskirch, C. Barbraud, T. Micol, Seabird mortality in the Patagonian toothfish longline fishery around Crozet and Kerguelen Islands. *CCAMLR Sci.* **12**, 53–80 (2005).

31. K. Delord, N. Gasco, C. Barbraud, H. Weimerskirch, Multivariate effects on seabird bycatch in the legal Patagonian toothfish longline fishery around Crozet and Kerguelen Islands. *Polar Biol.* **33**, 367–378 (2010).
32. G. N. Tuck, T. Polacheck, C. M. Bulman, Spatio-temporal trends of long line fishing effort in the Southern Ocean and implications for seabird bycatch. *Biol. Conserv.* **114**, 1–27 (2003).
33. E. L. Gilman, Bycatch governance and best practice mitigation technology in global tuna fisheries. *Mar. Policy* **35**, 590–609 (2014).
34. E. F. Melvin, T. J. Guy, L. B. Read, Best practice seabird bycatch mitigation for pelagic longline fisheries targeting tuna and related species. *Fish. Res.* **149**, 5–18 (2014).
35. H.-W. Huang, K.-M. Liu, Bycatch and discards by Taiwanese large-scale tuna longline fleets in the Indian Ocean. *Fish. Res.* **106**, 261–270 (2010).
36. B. Worm, H. K. Lotze, R. A. Myers, Predator diversity hotspots in the blue ocean. *Proc. Natl. Acad. Sci. U.S.A.* **100**, 9884–9888 (2003).
37. W. Montevecchi *et al*., Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. *Biol. Conserv.* **156**, 62–71 (2012).
38. M. Le Corre *et al*., Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean. *Biol. Conserv.* **156**, 83–93 (2012).
39. R. L. Lewison *et al*., Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 5271–5276 (2014).
40. T. R. Wahl, D. Heinemann, Seabirds and fishing vessels: Co-occurrence and attraction. *Condor* **81**, 390–396 (1979).
41. H. Skov, J. Durinck, Seabird attraction to fishing vessels is a local process. *Mar. Ecol. Prog. Ser.* **214**, 289–298 (2001).
42. H. Weimerskirch, N. Brothers, P. Jouventin, Population dynamics of wandering albatross *Diomedea exulans* and Amsterdam albatross *D. amsterdamensis* in the Indian Ocean and their relationships with long-line fisheries: Conservation implications. *Biol. Conserv.* **79**, 257–270 (1997).
43. H. Weimerskirch *et al*., Status and trends of albatrosses in the French Southern Territories, Western Indian Ocean. *Polar Biol.* **41**, 1963–1972 (2018).
44. D. Grémillet *et al*., Radar detectors carried by Cape gannets reveal surprisingly few fishing vessel encounters. *PLoS One* **14**, e0210328 (2019).
45. N. Queiroz *et al*., Global spatial risk assessment of sharks under the footprint of fisheries. *Nature* **572**, 461–466 (2019).
46. R. L. Lewison, S. A. Freeman, L. B. Crowder, Quantifying the effects of fisheries on threatened species: The impact of pelagic longlines on loggerhead and leatherback sea turtles. *Ecol. Lett.* **7**, 221–231 (2004).