Fine-scale interactions between boats and large albatrosses indicate variable susceptibility to bycatch risk according to species and populations

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Fine-scale interactions between boats and large albatrosses indicate variable susceptibility to bycatch risk according to species and populations

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Abstract

Many seabirds are attracted to fishing boats where they exploit foraging opportunities which often involve bycatch-related mortality. Bycatch risk is generally estimated by overlapping seabirds foraging ranges with coarse-scale monthly maps of fishing efforts. A more direct estimation would be the time birds spend attending fishing boats.

Here we matched data from Automatic Identification Systems from all declared boats in the Southern Ocean, with 143 simultaneous foraging trips from all populations of large albatrosses (*Diomedea amsterdamensis* and *Diomedea exulans*) breeding in the Indian Ocean (Marion, Crozet, Kerguelen, Amsterdam islands). We quantified and compared real-time co-occurrence between boats and albatrosses, at different scales (100, 30 and 5km). We also examined to what extent co-occurrence at a large-scale (5x5° grid cell) predicted fine-scale attendance (5km).

Albatrosses on average spent about 3h per trip attending fishing boats (<5km) at both Amsterdam and Marion and about 30h per trip at Kerguelen. In all populations >90% of declared fishing boat attendance occurred within Economic Exclusive Zones (EEZ) where bycatch mitigation measures are more strictly enforced. Outside EEZs, birds from all populations also significantly attended non-fishing boats. Fishing boat density at large scales (5x5°, 100km) poorly predicted time spent attending fishing boats (<5km) across populations.

Our results indicate a large variation in fishing boat density within foraging ranges of different populations, and in time spent attending boats. We discuss the pros and cons of using large-scale analyses and how they might be improved to better estimate bycatch risks in seabirds when fine-scale data is available particularly for conservation purpose on those highly threatened species.

Key words: albatross populations; biologging; bycatch assessment; ecological trap; fine-scale interaction; fisheries.

Introduction

In marine ecosystems, together with climate change, industrial fisheries constitute the main driver of ecological deterioration (Pauly et al., 2002). Fisheries interact with marine predators mainly by competing for resources (Cury et al., 2011; Grémillet et al., 2018) and by inducing mortality through bycatch of non-target species (Lewison et al., 2004). Fisheries can also facilitate access to prey for higher predators or provide additional food resources (Oro et al., 2013). For all these reasons many species of seabirds and marine mammals are attracted to fishing boats (Votier et al., 2004; Read, 2008; Brothers et al., 2010; Bugoni, McGill, & Furness, 2010) in search of foraging opportunities associated with fishing bait or discards (Votier et al., 2004; Bicknell et al., 2013a). However, the associated bycatch is one of the primary threats for seabird populations around the world (Croxall et al., 2012). Moreover in some seabird populations the poor quality of these food resources negatively affect reproductive success (Gremillet et al., 2008; Le Bot, Lescroël, & Grémillet, 2018a). Another concern is that populations heavily reliant on fishing vessels for food resources may be negatively impacted by changes in fishing policies (Bicknell et al., 2013b).

Bycatch is the most important threat for albatrosses and large petrels while at sea with high levels of mortality often induced by long-line fisheries (Delord et al., 2005; Anderson et al., 2011; Croxall et al., 2012). In the Southern Ocean, albatrosses overlap extensively with long-line fisheries, targeting tuna in oceanic waters, and various species of bottom-dwelling fishes over shelves and shelf-edges, in international waters as well as the Economic Exclusive Zones (EEZ) of the respective countries. The extent of spatio-temporal overlap between different fisheries and albatross foraging grounds has been inferred to represent mortality risk for various populations (Bertrand et al., 2012; Clay et al., 2019; Heerah et al., 2019). However, information on fisheries location is generally available at a large scale, especially in international waters. For example, global fishing efforts provided by Regional Fisheries Management Organisations for tuna and billfishes is only available at a monthly and by 5x5° cell resolution (Clay et al., 2019; Heerah et al., 2019). This approach ignores the possibility that fisheries and seabirds could co-occur at a large scale without birds interacting with the fishing boats, particularly if they are not attracted by vessels (Clark et al., 2020). To better estimate mortality risk it is therefore necessary to complement these approaches with more direct information on the actual time birds spend attending fishing boats and how this varies spatially (Torres et al., 2013). This has been hampered in the past by difficulties in obtaining fine scale information on fishing vessel movements from fishing operators or authorities, with Vessel Monitoring System (VMS) information often being confidential (Votier et al., 2010) and restricted to confined EEZ territories.

In the Indian Ocean, large active longline tuna and Patagonian toothfish (*Dissostichus eleginoides*) fisheries (Delord et al., 2005) overlap with the foraging ranges of the two large albatross species (wandering - *Diomedea exulans* and Amsterdam - *Diomedea amsterdamensis*) breeding in the region (Henri Weimerskirch, Brothers, & Jouventin, 1997; Delord et al., 2005). The past decline of the former species has been attributed to bycatch associated with long-line fisheries (Brothers, 1991; Henri Weimerskirch, Brothers, & Jouventin, 1997; Nel et al., 2002). Despite mitigation measures that have been implemented by toothfish longline fisheries within the EEZs, which has resulted in a reduction in bycatch by this fishery (Delord et al., 2005; Henri Weimerskirch et al., 2018), there are still concerns of bycatch risk from long line fisheries and/or illegal or uncontrolled fisheries targeting tuna in international waters within this region (Brothers, 1991; Henri Weimerskirch, Brothers, & Jouventin, 1997; H. Weimerskirch et al., 2020). Moreover, within more regulated EEZ waters it is important to estimate the extent to which albatrosses of different species and populations spend interacting with toothfish long-liners, to better quantify potential sub-lethal issues of dependence and possibly poor foraging quality (Bicknell et al., 2013a; Le Bot, Lescroël, & Grémillet, 2018b).

In this study, we combined a large tracking data set of foraging albatrosses (H. Weimerskirch et al., 2020) with the locations and types of all declared boats from Automatic Identification System (AIS) in the southern Indian Ocean. GPS tracking data were collected in 2018/2019 on breeding adults from all four major populations of large albatrosses in the Indian Ocean. We spatio-temporally matched these datasets to estimate the degree of co-occurrence at various scales from seascape (<100km), through encounter (<30km) to attendance (<5km), following Weimerskirch et al. (2020). We particularly focused on the time spent attending fishing boats (<5km) as a potential proxy for bycatch and other boat-associated risks. We examined how it differed among individuals and populations, how it differed with different types of fishing and non-fishing boats present during the breeding season, and how it differed between EEZs around subantarctic islands and international waters where different fisheries operate with different mitigation measures. Finally, to assess to what extent co-occurrence at a larger-scale reflects co-occurrence at finer-scale and could be used as a proxy for bycatch risk, we compared the time spent attending fishing boats (<5km) to the encounter rate (30km) and the density of boats in the seascape (<100km) as well as to another, more widely used method of aggregating boat data by Regional Fisheries Management Organisations (RFMO) 5x5° grid. We 1) hypothesized that there is a large variation in the levels of exposure to boats according to albatrosses' foraging zones and range, 2) tested to what extent it resulted in variation in the time spent attending boats and 3) tested whether large scale 5x5° grid methods provide an adequate reflection of the attendance to boats and therefore the risk of bycatch. We then discuss implications for bycatch and sub-lethal risks to the different populations.

Materials and methods

Field sites

Fieldwork was carried out in French southern territory (Crozet, Kerguelen & Amsterdam) during the course of a large-scale Ocean Sentinel program between January and April within the 2018/2019 breeding season of large albatrosses in the Southern Indian Ocean (H. Weimerskirch et al., 2020). We deployed loggers on wandering albatrosses at Possession Island (Crozet Islands) and at the Kerguelen Islands, and on Amsterdam albatrosses at Amsterdam Island. During the same incubation season GPS loggers were deployed on wandering albatrosses on South Africa's Marion Island, Prince Edward Islands.

Loggers

On Crozet, Kerguelen and Amsterdam, Centurion loggers (65g) recording GPS location every 2 min were deployed on incubating birds for one or two successive foraging trips (H. Weimerskirch et al., 2020). On Marion, GPS loggers (IgotU, 60g) recording locations every 20 min were deployed for several trips during the incubation and brooding period. The loggers were attached to the back feathers with Tesa® Tape (Germany), and represented between 0.5 and 0.85% of large albatross body mass, much less than the maximum 3% recommended for loggers attached on flying seabirds (Phillips, Xavier, & Croxall, 2003).

GPS data and AIS Dataset

A total of 143 trips on incubating albatrosses was recorded, with 57 trips from 27 individuals on Marion Island, 10 trips from 8 individuals at Amsterdam, 49 trips from 49 individuals at Crozet and 27 trips from 24 individuals at Kerguelen.

After using speed filters (150 km.h-1; Weimerskirch et al., 2020), we divided tracks by trips (removing location on land) and we only used trips from the incubation period.

AIS data for all fishing and non-fishing boats (Fig. S1) were obtained from French satellite transmission society (*Collecte Localisation Satellites*) for the study period for the sector 10°-180°E, 20°-70°S through the Ocean sentinel program (H. Weimerskirch et al., 2020), providing a total of 120 million AIS locations. Through the AIS system, in addition to regular GPS locations (mean resolution of 10 min) we obtained continuous data on identification name, nationality, type of boat (fishing or not), and activity for all declared boats in the Southern Indian Ocean. AIS data and bird locations were spatio-temporally matched following Weimerskirch et al. (2020) to produce a dataset where all GPS locations of each bird from each population are associated to the presence/absence, number and types of boats transmitting AIS information within ranges of 100, 30 and 5 km from birds.

These different radius distances from birds are used to characterize the 'boat seascape' (within 100 kilometres around the tracked bird), the 'boats encountered' (30km) and the 'boats attended' (5km). The 30 km distance was used as it is the distance within which an albatross can visually detect a boat (Thiebault et al., 2014; J Collet, Patrick, & Weimerskirch, 2015; Pirotta et al., 2018). The 5km threshold is close to the distance at which wandering albatrosses are seen to engage in specific foraging behaviour around boats (3km; Collet et al., 2015) and is used to facilitate comparisons with previous studies that used radar detectors with a range detection of 5km (Weimerskirch et al., 2020, 2017).

We defined ‘events’ (attendance and encounter events) as periods of consecutive bird locations within the respective distances of at least one boat with time gap less than 2 hours. To compare sites, and accommodate the relatively coarse scale GPS sampling at Marion Island, we removed all events (attendance and encounter) lasting less than 20 min. This procedure also limits the effects of uncertainties on “instantaneous” bird-boat distances (H. Weimerskirch et al., 2020). We also removed the few incomplete trips for presenting trip statistics (Table 1).

To compare with other studies using large scales 5x5°of fishing effort provided by RFMOs (Clay et al., 2019; Heerah et al., 2019), we merged all AIS locations present during the study period within grid cells of 5x5° (Fig. S1).

Environmental variables

AIS data do not provide detailed information on the type of fishing gears nor the mitigation measures employed by fishing boats. We tried to further infer these information from the waters they operated in. We added bathymetry data to each bird location (R package ‘marmap’, Pante and Simon-Bouhet, 2013), which was extracted from ‘ETOPO1 Global Relief Model’ from ‘National Oceanic and Atmospheric). We used it to categorize bird locations as on a shelf or a shelf-edge (above -2000 m), where mainly benthic fishes are targeted, or not, where tunas are the main target. We also considered whether locations were within EEZ or not (data from http://www.marineregions.org) and separately considered the time in attendance for specific EEZs with enforced mitigation measures within the range of our populations (Crozet, Kerguelen, Heard, McDonald Saint-Paul and Amsterdam Islands). Finally, from estimates of the locations of the polar front (Moore, Abbott, & Richman, 1999) and the subtropical front (Belkin & Gordon, 1996) we further categorized bird locations into Antarctic, subantarctic and subtropical waters.

Analyses

For visualization purposes, we used kernel Utilization Distributions (UDs 50 and 90%), using the R package 'adehabitatHR' (smoothing parameters, h=1 degree).

To compare different parameters (Table 1) between each population, we used linear mixed model or generalized linear mixed models (depending on the distribution, using R package "fitdistrPlus"). Negative binomial family were used for over-dispersed count data and binomial family for ratio data (R packages 'lme4' and "lmerTest"). Bird individual identities were used as random factors. We further used post-hoc tests (Tukey tests, R package multicomp) and Holm-Bonferroni correction for P values. We used Chi^2 test to compare distributions of the number of trips with or without boat interaction between populations.

To compare AIS data to time birds spent per 5x5° grid, we summed AIS locations (for all types of boat or only for fishing boat) per grid cell used by each study population during their respective incubation-period months (April for Amsterdam birds, January and February for Crozet and Kerguelen birds, and February and March for Marion birds). Then, we used Pearson correlation to examine whether those aggregated AIS data are related to the time spent by birds in general, with boats in their seascape (<100km), with boats encountered (<30km) and with boats attended (<5km) in the same 5x5° grid cells.

Results

For the 143 trips recorded during incubation, there were no significant differences between populations in the duration of foraging trips but mean maximum distance from the colony differed between Kerguelen (shortest) and Marion (longest) (Table 1).

Birds from Kerguelen spent more time foraging within EEZs (74%±32, Table 1) than birds from Crozet (57%±35), Amsterdam (39%±41) and Marion (36%±24). Amsterdam and Marion birds spent less time foraging over shelf waters (20%±29 and 11%±15 respectively) as compared to Crozet (40%±33) and Kerguelen birds (65%±29) (Fig. 1) (Table 1 and Table S1 for test values).

Amsterdam albatrosses spent most of their time in subtropical waters (97%±07) whereas the three wandering albatross populations foraged mainly in subantarctic waters (57%±31 to 78%±30) (Fig. 1) (Table 1 and Table S1 for test values).

Among the 143 trips recorded, the percentages of trips with at least one boat within 100 km (boat seascape), were significantly different between populations, ranging from 68% to 100% (Chi^2, 3 = 24.9; p value = 1.5e-05) (Table 2). The percentage of trips with boats encountered (within 30 km) also varied significantly between sites, from 63 to 85% (Chi^2, 3 = 9.08; p value = 0.028) (Table 2). Finally, the percentage of trips with attendance (within 5 km) of boats were also significantly different between sites, varying from 47 to 73 % (Chi^2, 3 = 8.01; p value = 0.046) (Table 2).

The number of encounters and attendance events per trip, when considering fishing boats and other boats together (transport, tankers, etc.) was similar between populations (Table 1 and Table S1 for test values). Kerguelen birds spent more time on average per trip within 30km of all types of boats (53h±62), within 5km of all type of boats (31h±38) and within 5 km of fishing boats (30.6h±39) (Fig. 2a) than birds from other populations (Table 1 and Table S1 for test values). Similarly, Kerguelen birds spent significantly more time attending boats inside EEZs (with mitigation measures) than birds from other populations. However, outside EEZ (where mitigation measures are less controlled) the different populations spent similar time attending AIS-recorded boats of all types, and similar time attending AIS-recorded fishing boats (Table 1 and Table S1 for test values).

Based on all location, Amsterdam birds on average had the most number of boats (1.9±5) and the most number of fishing boats (0.83±1.9) in their seascapes (<100km), at least twice as much as other populations (Table 1 and Table S1 for test values). However at Kerguelen birds on average had the most number of boat encounters (<30km: 0.2±0.4), the most number of boats attended (<5km: 0.1±0.3, Fig. 2b) and the highest ratio of the number of boats attended relative to the number boats in the seascape (0.3±0.5), most of the time by a factor of 5-10 fold compared to other populations (Table 1 and Table S1 for test values).

Marion and Amsterdam birds had a smaller proportion of fishing versus non-fishing boats in their seascapes (<100km) compared to other populations (Table 1 and Table S1 for test values). Marion birds had a significantly lower proportion of fishing boats among encountered boats (<30km) than Crozet and Kerguelen and slightly less than Amsterdam. The proportion of fishing boats among attended boats (<5km) was not different between Marion, Amsterdam and Crozet birds (0.22±0.4, 0.64±0.4 and 0.76±0.4, respectively), but it was lower than for Kerguelen birds (0.95±0.2, Table 1 and Table S1 for test values).

Finally, we found that at all locations, birds attended only a small proportion of the total number of boats in their seascapes: 30%±45 for Kerguelen birds which was significantly higher than for Crozet birds (7%±24) and for Marion and Amsterdam birds (4% ±0.19; Table 1 and Table S1 for test values).

For all four populations, there were no significant correlations between the time spent by birds per 5x5° grid cells (in general, with boats in their seascape, with boats encountered and with boats attended) and between the number of AIS signals per 5x5° grid cells. This applied when considering all types of boats as well as fishing boats only (Table 3 and Fig. S1).

Discussion

Our study clearly indicates strong differences between populations in the time spent attending boats, with different associated bycatch risks (Fig. 2a). Furthermore, we clearly show that these variations in time spent attending boats are not a simple linear function of the density of boats in the seascape, as previous methods aimed at assessing bycatch risk have assumed. Indeed, we have shown that using AIS data combined with fine scale GPS tracking of seabirds can provide a considerably more reliable estimate of bycatch risks, through the documentation of the actual time birds spend interacting at a fine scale with different types of declared boats. Indeed, most previous studies used monthly maps of the number of hooks deployed within aggregated 5x5° cells (around 560x560km in our region) to estimate risks incurred by foraging birds (Clay et al., 2019; Heerah et al., 2019), but here we show that analyses at this scale do not correlate at all with time spent interacting with boats.

Overall, we found that all four populations spent considerably more time attending fisheries boats within EEZs (with bycatch mitigation measures) than in international waters. On average, birds from all populations spent less than 1h per trip attending declared fishing boats outside EEZs where bycatch mitigation measures are generally adopted leading to low seabirds' mortalities. While it means that at least 3 out of the 4 studied populations are indeed at risk of bycatch from these declared fleets outside EEZs (where no bycatch mitigation measures are taken), birds seem to spend limited time attending them. Important to note is that this result could potentially be very different if non-declared boats (without AIS) could also be included. Indeed, illegal, undeclared and unregulated fleets may represent up to 30% of boat encounters for breeding large albatrosses (H. Weimerskirch et al., 2020). The lack of information on these boats can partly be remedied by using new loggers that can detect radar emission of boats up to 5km away (Weimerskirch, Filippi, Collet, Waugh, & Patrick, 2017). However, AIS data provides additional information on boat identity and also on a larger scale boat seascape around birds, so that more accurate results could be reached by combining the two methods (radar detectors were not available for Marion birds in the present study).

AIS data revealed that the four populations of large albatrosses breeding within the Indian Ocean foraged in very different boat seascapes. Yet, the time spent interacting with fishing boats within or beyond EEZs could not be predicted by the respective boat densities with the foraging ranges of the different populations. Fishing boats in the area mainly fall within two categories: toothfish longline fisheries operating on subantarctic shelves and tuna longlining fisheries operating in subtropical waters (Corbeau et al., 2019). In addition, many non-fishing boats (cargo, tankers) transit through subtropical waters between Africa, Asia and Australia. Birds from Marion had the least contact with boats, with a large proportion of trips without boat encounters, yet most attended boats were not associated with fisheries. This can potentially be explained by the absence of a surrounding shelf and the small scale of the declared toothfish fishery in the region in comparison to Crozet and Kerguelen (H. Weimerskirch et al., 2020). Furthermore, birds from Marion spent a relatively low proportion of their foraging time in subtropical waters (in contrast to Amsterdam birds). At the opposite end, Amsterdam birds ranged in the densest boat seascape, both in terms of the general boat density and in terms of fishing boats density. This is of particular concern for this endangered species with less than 60 pairs breeding annually on Amsterdam Island (Thiebot et al., 2015; Heerah et al., 2019). Yet, birds from Marion and Amsterdam populations eventually spent very similar average amounts of time with declared fishing boats both within or outside EEZs (with different bycatch mitigation measures). In contrast, compared to Marion and Amsterdam populations, Kerguelen birds spent considerably more time with fishing boats and mostly within EEZs with much lower boat densities and Crozet birds appeared to spend more time with fishing boats both outside and within EEZs. Moreover, we have shown that large-scale overlap analyses (5x5°) of AIS data was not related to the proxy of fine-scale bycatch risk (Table 3). It is therefore very clear that the density of (fishing) boats within the foraging range does not linearly translate into time spent attending boats.

This discrepancy between boat density in the foraging range of seabirds and the actual time birds spent attending fishing boats calls for caution when estimating bycatch risk from large-scale overlap data. AIS data is costly but it may be more easily accessible to researchers than the often confidential and geographically-restricted VMS data (Votier et al., 2010) to allow for fine-scale analyses. However large-scale overlap analyses will still be needed in particular when bird tracking data is available at lower resolution than that offered by GPS tracking devices (Clay et al., 2019a). This may be the case for many studies using GLS devices on non-breeding individuals (juveniles, failed breeders, adults in winter or on sabbatical, etc.) or for small species for which relatively large GPS device deployment could be problematic (Le Corre et al., 2012; Delord et al., 2014). It would thus be useful to understand why a higher boat density does not necessarily translate into more time spent by seabirds attending boats, and under what circumstances this applies, to improve bycatch risk estimation from large-scale data.

An intriguing consideration raised by our results relevant to improving bycatch risk estimations from large-scale data, is what we may call the dilution-shield hypothesis. An increasing boat density may increase the encounter probability (Julien Collet, Patrick, & Weimerskirch, 2017), but when a bird starts to attend and exploit a boat it reduces its exploration time and chances of encountering further boats. Indeed, we clearly show that the densest the boat seascape is, the lower the ratio of all boats in the seascape being actually approached by birds (Table 1). Beyond a certain value, boat density may become less important to consider than which boat(s) birds are attending. In the Mediterranean Sea, shearwaters were observed to interact less with longliners when trawlers were present than when trawlers were absent (Soriano-Redondo et al., 2016). In our study, Amsterdam albatrosses ranged by far in the densest fishing boat seascape, but also in the densest non-fishing boat seascape. In contrast, Kerguelen birds did not range in a very dense fishing boat area, but virtually all boats on the Kerguelen shelf are fishing boats (Table 1). If birds are not strongly selective on the boats they attend after encounters, non-fishing boats might dilute the bycatch risk and act as a shield against more dangerous boats. Indeed we found that outside of EEZs, birds spent most of their time in attendance of boats not associated with fisheries: 100% for Kerguelen, 93% for Amsterdam, 81% for Marion and 35% for Crozet (within EEZs only fishing boats were identified). Moreover, within all four populations, the ratio of fishing in relation to non-fishing boats remained relatively similar across the three investigated scales (5, 30 and 100km, Table 1), suggesting low selectivity. It may be worth further investigating this hypothesis because if this is correct, bycatch risk estimations from large scale overlap data (Clay et al., 2019; Heerah et al., 2019) might relatively easily be improved by considering not only fishing boat density but also non-fishing boat density within the foraging ranges of seabirds.

Boats may also cause other non-lethal issues beyond bycatch (nutritional and/or dependence issues), especially if they become an important part of birds' time budgets (Fig. 2b) and/or diet. To our knowledge, there are very few studies that have looked at how fisheries-independent boats may impact foraging success and behavior in seabirds. However, it seems that our studied birds spent a low fraction of their foraging time attending them. Of greater concern is the large amount of time Kerguelen birds seem to spend attending the toothfish longline fishery operating around their breeding ground. The nature, quality and amount of food albatrosses can obtain from these toothfish fisheries are unclear considering bycatch mitigation measures that are implemented. However, Kerguelen birds appear to be more dependent on these boats than the most studied Crozet population.

An important question about bycatch risk is whether the large differences we observe in the time incubating birds spent attending different types of fishing boats across populations may be related to differences in population trends. Amsterdam albatrosses have been increasing since the 1980s at a high rate, suggesting that they suffer minimal if any mortality from fisheries (Rivalan, Barbraud, Inchausti, & Weimerskirch, 2010; Weimerskirch et al., 1997). Although they forage in zones with high densities of both fishing and non-fishing boats, birds do not seem to be particularly attracted by fishing boats: the low interaction to boats may explain why this population has been able to increase steadily over the past four years. The three other populations have shown similar trends until about 15 years ago, with a steep decline in the 1970s and early 1980 followed by a partial recovery (Nel et al., 2002; Weimerskirch et al., 1997). Since then, the population on Marion has been increasing, whereas Kerguelen and Crozet populations are stable (Ryan, Jones, Dyer, Upfold, & Crawford, 2009; Weimerskirch et al., 2018). This difference in population dynamics of the wandering albatross populations could be related to the lower encounter and attendance rates of Marion birds compared to Crozet and Kerguelen birds.

Seabirds are one of the animal groups with the largest proportion of threatened species and there has been much effort globally to better understand causative mechanisms behind declining populations for conservation purposes. In this paper, we proposed a simple method for estimating fine scale interactions between seabirds and boats with AIS. This method is easily implemented through the combination of seabirds GPS tracks, now routinely collected globally (Burger & Shaffer, 2008; Le Corre et al., 2012), and AIS data, which is readily available (International Maritime Organisation).

With this method we provided the most direct and comprehensive assessment to date of bycatch risk for large albatrosses breeding in the Indian Ocean, including for one of the most threatened bird species. We illustrated the pros and cons of using AIS data for such estimations, compared to other existing methods (large-scale overlap analyses and/or use of embarked radar detectors). Importantly we showed that fishing boat density may not be a good proxy to predict time spent attending boats and bycatch risk, and we proposed a general hypothesis of shield effect from other types of boats to explain this discrepancy. Our results also reveal extensive variations in the time and proportion of foraging time populations spent attending various types of boats, which may cause other non-lethal issues beyond bycatch risks, especially in the Kerguelen population.

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Data accessibility

Data are available in figshare at doi: 10.6084/m9.figshare.10289096 (Weimerskirch, Collet, Corbeau, Pajot, Hoarau, Marteau, Filippi, Patrick, et al., 2019)

Authors' contributions

HW conceived the project, AC, JC, FO, HW and PP contributed data and/or did field work and prepared the data, JC merged AIS data to tracking data, AC performed all the other analyses, AC and HW wrote the original paper and all authors commented on earlier drafts.

References

Anderson, O., Small, C., Croxall, J., Dunn, E., Sullivan, B., Yates, O., & Black, A. (2011). Global seabird bycatch in longline fisheries. *Endanger. Species Res.* **14**, 91–106.

Belkin, I. M., & Gordon, A. L. (1996). Southern Ocean fronts from the Greenwich meridian to Tasmania. *J. Geophys. Res. Oceans* **101**, 3675–3696.

Bertrand, S., Joo, R., Arbulu Smet, C., Tremblay, Y., Barbraud, C., & Weimerskirch, H. (2012). Local depletion by a fishery can affect seabird foraging. (M. Frederiksen, Ed.)*J. Appl. Ecol.* **49**, 1168–1177.

Bicknell, A. W. J., Oro, D., Camphuysen, K. C. J., & Votier, S. C. (2013a). Potential consequences of discard reform for seabird communities. (J. Blanchard, Ed.)*J. Appl. Ecol.* **50**, 649–658.

Bicknell, A. W. J., Oro, D., Camphuysen, K. C. J., & Votier, S. C. (2013b). Potential consequences of discard reform for seabird communities. (J. Blanchard, Ed.)*J. Appl. Ecol.* **50**, 649–658.

Brothers, N. (1991). Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. *Biol. Conserv.* **55**, 255–268.

Brothers, N., Duckworth, A. R., Safina, C., & Gilman, E. L. (2010). Seabird Bycatch in Pelagic Longline Fisheries Is Grossly Underestimated when Using Only Haul Data. (S. J. Bograd, Ed.)*PLoS ONE* **5**, e12491.

Bugoni, L., McGill, R. A. R., & Furness, R. W. (2010). The importance of pelagic longline fishery discards for a seabird community determined through stable isotope analysis. *J. Exp. Mar. Biol. Ecol.* **391**, 190–200.

Burger, A. E., & Shaffer, S. A. (2008). APPLICATION OF TRACKING AND DATA-LOGGING TECHNOLOGY IN RESEARCH AND CONSERVATION OF SEABIRDS. *The Auk* **125**, 253–264.

Clark, B. L., Vigfúsdóttir, F., Jessopp, M. J., Burgos, J. M., Bodey, T. W., & Votier, S. C. (2020). Gannets are not attracted to fishing vessels in Iceland—potential influence of a discard ban and food availability. (K. Camphuysen, Ed.)*ICES J. Mar. Sci.* **77**, 692–700.

Clay, T. A., Small, C., Tuck, G. N., Pardo, D., Carneiro, A. P. B., Wood, A. G., Croxall, J. P., Crossin, G. T., & Phillips, R. A. (2019). A comprehensive large-scale assessment of fisheries bycatch risk to threatened seabird populations. (V. Paiva, Ed.)*J. Appl. Ecol.*

Collet, J, Patrick, S., & Weimerskirch, H. (2015). Albatrosses redirect flight towards vessels at the limit of their visual range. *Mar. Ecol. Prog. Ser.* **526**, 199–205.

Collet, Julien, Patrick, S. C., & Weimerskirch, H. (2017). Behavioral responses to encounter of fishing boats in wandering albatrosses. *Ecol. Evol.* **7**, 3335–3347.

Corbeau, A., Collet, J., Fontenille, M., & Weimerskirch, H. (2019). How do seabirds modify their search behaviour when encountering fishing boats? (D. Hyrenbach, Ed.)*PLOS ONE* **14**, e0222615.

Croxall, J. P., Butchart, S. H. M., Lascelles, B., Stattersfield, A. J., Sullivan, B., Symes, A., & Taylor, P. (2012). Seabird conservation status, threats and priority actions: a global assessment. *Bird Conserv. Int.* **22**, 1–34.

Cury, P. M., Boyd, I. L., Bonhommeau, S., Anker-Nilssen, T., Crawford, R. J. M., Furness, R. W., Mills, J. A., Murphy, E. J., Osterblom, H., Paleczny, M., Piatt, J. F., Roux, J.-P., Shannon, L., & Sydeman, W. J. (2011). Global Seabird Response to Forage Fish Depletion--One-Third for the Birds. *Science* **334**, 1703–1706.

Delord, K., Barbraud, C., Bost, C. A., Cherel, Y., Guinet, C., & Weimerskirch, H. (2014). Atlas of top predators from French Southern Territories in the Southern Indian Ocean. CNRS.

Delord, K., Gasco, N., Weimerskirch, H., Barbraud, C., & Micol, T. (2005). Seabird mortality in the Patagonian toothfish longline fishery around Crozet and Kerguelen Islands, 2001–2003. *Ccamlr Sci.* **12**, 53–80.

Gremillet, D., Pichegru, L., Kuntz, G., Woakes, A. G., Wilkinson, S., Crawford, R. J. M., & Ryan, P. G. (2008). A junk-food hypothesis for gannets feeding on fishery waste. *Proc. R. Soc. B Biol. Sci.* **275**, 1149–1156.

Grémillet, D., Ponchon, A., Paleczny, M., Palomares, M.-L. D., Karpouzi, V., & Pauly, D. (2018). Persisting Worldwide Seabird-Fishery Competition Despite Seabird Community Decline. *Curr. Biol.* **28**, 4009-4013.e2.

Heerah, K., Dias, M. P., Delord, K., Oppel, S., Barbraud, C., Weimerskirch, H., & Bost, C. A. (2019). Important areas and conservation sites for a community of globally threatened marine predators of the Southern Indian Ocean. *Biol. Conserv.* **234**, 192–201.

Le Bot, T., Lescroël, A., & Grémillet, D. (2018a). A toolkit to study seabird–fishery interactions. (S. Votier, Ed.)*ICES J. Mar. Sci.* **75**, 1513–1525.

Le Bot, T., Lescroël, A., & Grémillet, D. (2018b). A toolkit to study seabird–fishery interactions. (S. Votier, Ed.)*ICES J. Mar. Sci.* **75**, 1513–1525.

Le Corre, M., Jaeger, A., Pinet, P., Kappes, M. A., Weimerskirch, H., Catry, T., Ramos, J. A., Russell, J. C., Shah, N., & Jaquemet, S. (2012). Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean. *Biol. Conserv.* **156**, 83–93.

Lewison, R., Crowder, L., Read, A., & Freeman, S. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol. Evol.* **19**, 598–604.

Moore, J. K., Abbott, M. R., & Richman, J. G. (1999). Location and dynamics of the Antarctic Polar Front from satellite sea surface temperature data. *J. Geophys. Res. Oceans* **104**, 3059–3073.

Nel, Deon. C., Ryan, P. G., Nel, J. L., Klages, N. T. W., Wilson, R. P., Robertson, G., & Tuck, G. N. (2002). Foraging interactions between Wandering Albatrosses Diomedea exulans breeding on Marion Island and long-line fisheries in the southern Indian Ocean: Foraging interactions in albatrosses. *Ibis* **144**, E141–E154.

Oro, D., Genovart, M., Tavecchia, G., Fowler, M. S., & Martínez-Abraín, A. (2013). Ecological and evolutionary implications of food subsidies from humans. (B. Worm, Ed.)*Ecol. Lett.* **16**, 1501–1514.

Pante, E., & Simon-Bouhet, B. (2013). marmap: A Package for Importing, Plotting and Analyzing Bathymetric and Topographic Data in R. (G. J.-P. Schumann, Ed.)*PLoS ONE* **8**, e73051.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R., & Zeller, D. (2002). Towards sustainability in world fisheries. *Nature* **418**, 689–695.

Phillips, R. A., Xavier, J. C., & Croxall, J. P. (2003). Effects of satellite transmitters on albatrosses and petrels. *The Auk* **120**, 1082–1090.

Pirotta, E., Edwards, E. W. J., New, L., & Thompson, P. M. (2018). Central place foragers and moving stimuli: A hidden-state model to discriminate the processes affecting movement. (L. Börger, Ed.)*J. Anim. Ecol.* **87**, 1116–1125.

Read, A. J. (2008). The looming crisis: interactions between marine mammals and fisheries. *J. Mammal.* **89**, 541–548.

Rivalan, P., Barbraud, C., Inchausti, P., & Weimerskirch, H. (2010). Combined impacts of longline fisheries and climate on the persistence of the Amsterdam Albatross Diomedia amsterdamensis. *Ibis* **152**, 6–18.

Ryan, P. G., Jones, M. G., Dyer, B. M., Upfold, L., & Crawford, R. J. (2009). Recent population estimates and trends in numbers of albatrosses and giant petrels breeding at the sub-Antarctic Prince Edward Islands. *Afr. J. Mar. Sci.* **31**, 409–417.

Soriano-Redondo, A., Cortés, V., Reyes-González, J. M., Guallar, S., Bécares, J., Rodríguez, B., Arcos, J. M., & González-Solís, J. (2016). Relative abundance and distribution of fisheries influence risk of seabird bycatch. *Sci. Rep.* **6**, 37373.

Thiebault, A., Mullers, R. H. E., Pistorius, P. A., & Tremblay, Y. (2014). Local enhancement in a seabird: reaction distances and foraging consequence of predator aggregations. *Behav. Ecol.* **25**, 1302–1310.

Thiebot, J.-B., Delord, K., Barbraud, C., Marteau, C., & Weimerskirch, H. (2015). 167 individuals versus millions of hooks: bycatch mitigation in longline fisheries underlies conservation of Amsterdam albatrosses: Amsterdam Albatrosses and Longline Fisheries. *Aquat. Conserv. Mar. Freshw. Ecosyst.* n/a-n/a.

Torres, L., Sagar, P., Thompson, D., & Phillips, R. (2013). Scaling down the analysis of seabird-fishery interactions. *Mar. Ecol. Prog. Ser.* **473**, 275–289.

Votier, S. C., Bearhop, S., Witt, M. J., Inger, R., Thompson, D., & Newton, J. (2010). Individual responses of seabirds to commercial fisheries revealed using GPS tracking, stable isotopes and vessel monitoring systems. *J. Appl. Ecol.* **47**, 487–497.

Votier, S. C., Furness, R. W., Bearhop, S., Crane, J. E., Caldow, R. W. G., Catry, P., Ensor, K., Hamer, K. C., Hudson, A. V., Kalmbach, E., Klomp, N. I., Pfeiffer, S., Phillips, R. A., Prieto, I., & Thompson, D. R. (2004). Changes in fisheries discard rates and seabird communities. *Nature* **427**, 727–730.

Weimerskirch, H., Collet, J., Corbeau, A., Pajot, A., Hoarau, F., Marteau, C., Filippi, D., & Patrick, S. C. (2020). Ocean sentinel albatrosses locate illegal vessels and provide the first estimate of the extent of nondeclared fishing. *Proc. Natl. Acad. Sci.* 201915499.

Weimerskirch, H., Collet, J., Corbeau, A., Pajot, A., Hoarau, F., Marteau, C., Filippi, D., Patrick, S. C., Pistorius, P., Orgeret, F., & Joo, R. (2019). Data_OCEAN_SENTINEL_Weimerskirch_et_al_2018_2019. *Figshare - Dataset.*

Weimerskirch, H., Filippi, D. P., Collet, J., Waugh, S. M., & Patrick, S. C. (2017). Use of radar detectors to track attendance of albatrosses at fishing vessels: Seabird-Fishery Interactions. *Conserv. Biol.*

Weimerskirch, Henri, Brothers, N., & Jouventin, P. (1997). 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.

Weimerskirch, Henri, Delord, K., Barbraud, C., Le Bouard, F., Ryan, P. G., Fretwell, P., & Marteau, C. (2018). Status and trends of albatrosses in the French Southern Territories, Western Indian Ocean. *Polar Biol.* **41**, 1963–1972.

Table

Table 1 – Differences between each site: mean and standard deviation of parameters and significance letters of Tuckey tests (same letter in different site mean no difference and different letters mean significant differences).

	Amsterdam ***(trips: n=10, 10 complete)***			**Crozet** ***(trips: n=49, 48 complete)***			**Kerguelen** ***(trips: n=27, 23 complete)***			**Marion** ***(trips: n=57, 53 complete)***		
	Mean	Standard deviation	Significance letter	Mean	Standard deviation	Significance letter	Mean	Standard deviation	Significance letter	Mean	Standard deviation	Significance letter
PER TRIP (n=143)												
Maximum distance from the colony (km)	1637.70	1281.10	AB	1177.90	813.90	AB	886.60	711.85	A	1424.70	660.54	B
Trip duration (day)	9.53	3.48	A	11.09	5.60	A	10.60	4.14	A	12.60	4.46	A
Ratio in EEZ	0.39	0.41	AC	0.57	0.35	AB	0.74	0.32	B	0.36	0.24	C
Ratio on shelf	0.20	0.29	AC	0.40	0.33	A	0.65	0.29	B	0.11	0.15	C
Ration in Antarctic waters	0.00	0.00	A	0.07	0.20	A	0.19	0.30	A	0.12	0.26	A
Ration in subantarctic waters	0.03	0.07	A	0.72	0.34	B	0.78	0.30	B	0.57	0.31	B
Ration in subtropical waters	0.97	0.07	A	0.21	0.32	BC	0.02	0.13	B	0.31	0.32	C
Number of encounters	5.10	7.61	A	3.06	2.18	A	2.89	2.65	A	4.23	5.45	A
Time in encounter (h)	19.04	23.28	A	17.08	18.36	A	53.30	62.82	B	11.91	21.96	A
Number of attendances	1.80	2.20	A	1.71	1.57	A	3.59	4.41	A	1.72	2.70	A
Time in attendance (h)	4.31	6.97	A	6.75	11.00	A	31.14	38.22	B	3.21	10.20	A
Time in attendance with fishing vessels (h)	3.16	7.56	A	6.68	11.31	A	30.63	39.27	B	2.64	10.31	A
Time in attendance in EEZ (h)	2.90	6.71	A	5.84	11.14	A	28.37	38.60	B	2.46	10.24	A
Time in attendance out EEZ (h)	1.42	2.40	A	0.91	2.74	A	2.77	11.56	A	0.75	1.58	A
Time in attendance with fishing vessels in EEZ (h)	2.82	6.75	A	5.84	11.14	A	28.36	38.60	B	2.45	10.24	A
Time in attendance with fishing vessels out EEZ (h)	0.11	0.28	A	0.60	2.66	A	0.00	0.00	A	0.14	0.68	A
Ratio of fishing vessels attended (5km)	0.64	0.43	AB	0.76	0.42	AB	0.95	0.23	A	0.22	0.37	B
Ratio of fishing vessels encountered (30km)	0.63	0.36	AB	0.76	0.40	A	0.92	0.28	A	0.17	0.32	B
Ratio of fishing vessels in seascape (100km)	0.43	0.27	A	0.75	0.36	B	0.92	0.23	B	0.16	0.29	A
PER LOCATION (n=619631)												
Number of boats attended (5km)	0.02	0.16	A	0.02	0.15	A	0.11	0.31	B	0.01	0.11	C
Number of boats encountered (30km)	0.19	0.84	A	0.06	0.26	B	0.23	0.43	C	0.05	0.26	B
Number of boats in seascape (100km)	1.99	5.08	A	0.29	0.60	B	0.40	0.60	C	0.35	1.11	D
Number of fishing vessels in seascape (100km)	0.83	1.93	A	0.21	0.51	B	0.39	0.60	C	0.07	0.33	D
Ratio of number of boats 5 km / 100 km	0.04	0.19	A	0.07	0.24	A	0.30	0.45	B	0.04	0.18	A

Table 2 – Number (and percentage) of trips per site with boats in seascapes (100km), encountered (30km) and attended (5km).

	Amsterdam *(n=10)*	Crozet *(n=49)*	Kerguelen *(n=27)*	Marion *(n=57)*	TOTAL (n=143)
With boats in seascape (100km)	9 (90%)	48 (97.96%)	27 (100%)	39 (68.42%)	**123 (86.01%)**
With boats encountered (30km)	8 (80%)	42 (85.71%)	23 (85.19%)	36 (63.16%)	**109 (76.22%)**
With boats attended (5km)	6 (60%)	36 (73.47%)	18 (66.67%)	27 (47.37%)	**87 (60.84%)**

Table 3 – Correlations (with p value of Pearson test) between the number of AIS signals (total and for fishing boats only) per 5x5° grid cells and the time spent by birds in same 5x5° grid cell (for a total time, for time with boats in seascape (<100km), for time with boats in encounter (<30km) and for time with boats in attendance (<5km)) for the active months of the different populations of albatrosses.

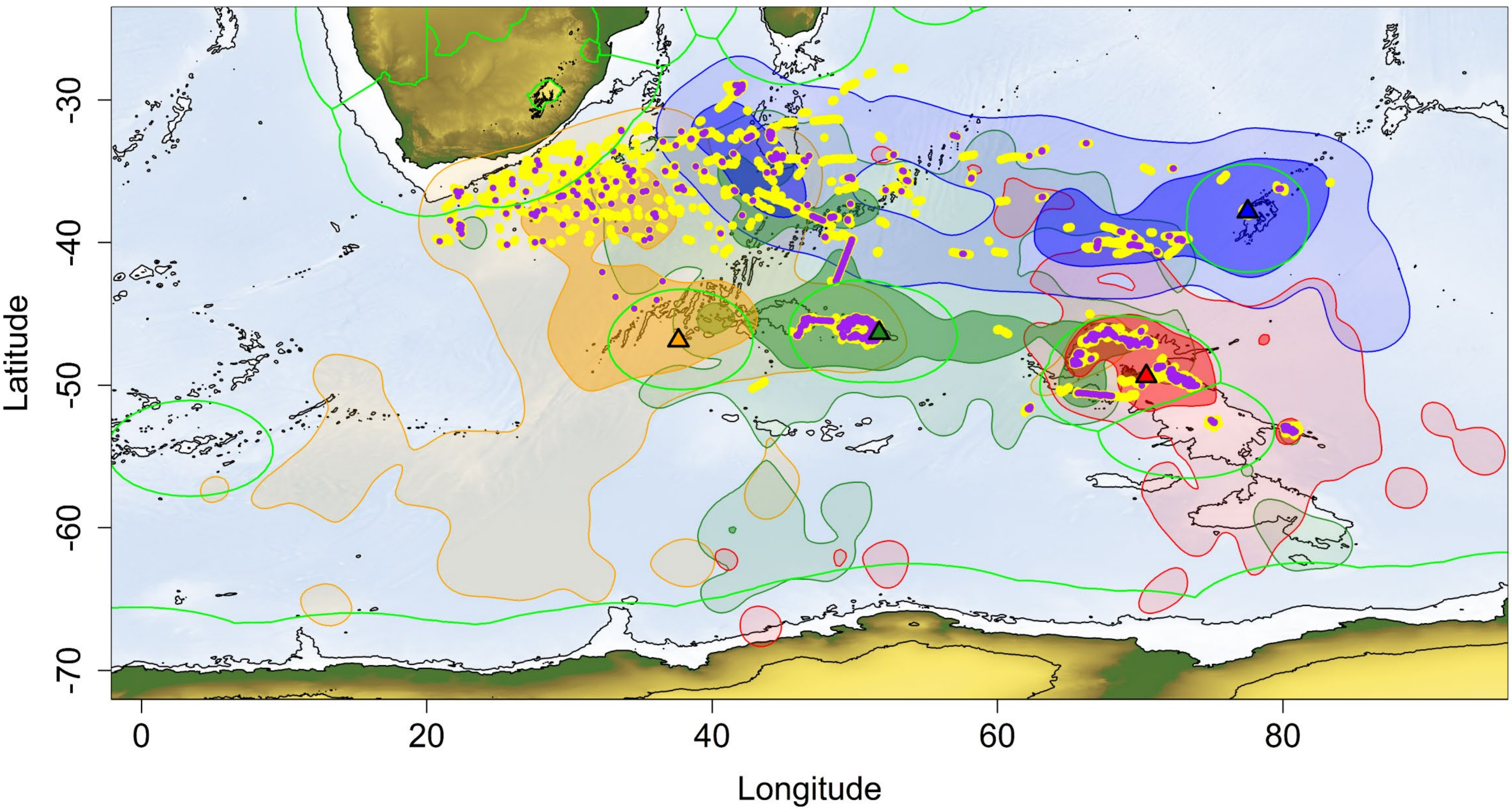
	Amsterdam (n=37 cells)		**Crozet (n=63 cells)**		**Kerguelen (n=41 cells)**		**Marion (n=54 cells)**	
ANALYSES FOR 5x5° GRID	**Number of AIS signals (April)**	**Number of AIS fishery signals (April)**	**Number of AIS signal (January & February)**	**Number of AIS fishery signals (January & February)**	**Number of AIS signals (January & February)**	**Number of AIS fishery signals (January & February)**	**Number of AIS signals (February & March)**	**Number of AIS fishery signals (February & March)**
Bird time spent in grid cell	-0.113 (p=0.52)	-0.113 (p=0.52)	-0.094 (p=0.48)	-0.094 (p=0.48)	-0.039 (p=0.81)	-0.056 (p=0.73)	-0.012 (p=0.94)	-0.012 (p=0.94)
Bird time spent with boat at 100km	0.062 (p=0.72)	0.062 (p=0.73)	-0.021 (p=0.87)	-0.021 (p=0.88)	0.026 (p=0.87)	0.008 (p=0.96)	0.199 (p=0.18)	0.199 (p=0.19)
Bird time spent in encounter	0.194 (p=0.27)	0.192 (p=0.28)	-0.029 (p=0.83)	-0.029 (p=0.83)	0.025 (p=0.88)	0.007 (p=0.97)	0.164 (p=0.28)	0.165 (p=0.28)
Bird time spent in attendance	-0.050 (p=0.78)	-0.052 (p=0.77)	-0.038 (p=0.78)	-0.037 (p=0.78)	0.018 (p=0.91)	0.002 (p=0.99)	-0.014 (p=0.93)	-0.014 (p=0.93)

Figures legends

Figure 1 - Map of the South Indian Ocean with kernel utilization distribution 50% (darker shade) and 90% (lighter shade) of birds for each site (triangles) (blue = Amsterdam, green = Crozet, red= Kerguelen, orange= Marion); yellow dots represent encounter events and purple dots, attendance events; isobaths: -2000 m (shelf), 0 m and +2000 m; light-green lines represent EEZ.

Figure 2 – Proxy of bycatch risk as **(a)** time spent per trip in attendance (within 5km) with fishing boats (hours) and **(b)** Number of boat attended (within 5 km) at any location; Mean and confidence interval (95%) of each site. Letters represent significant difference.

571 **Figures**



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573 **Figure 1**

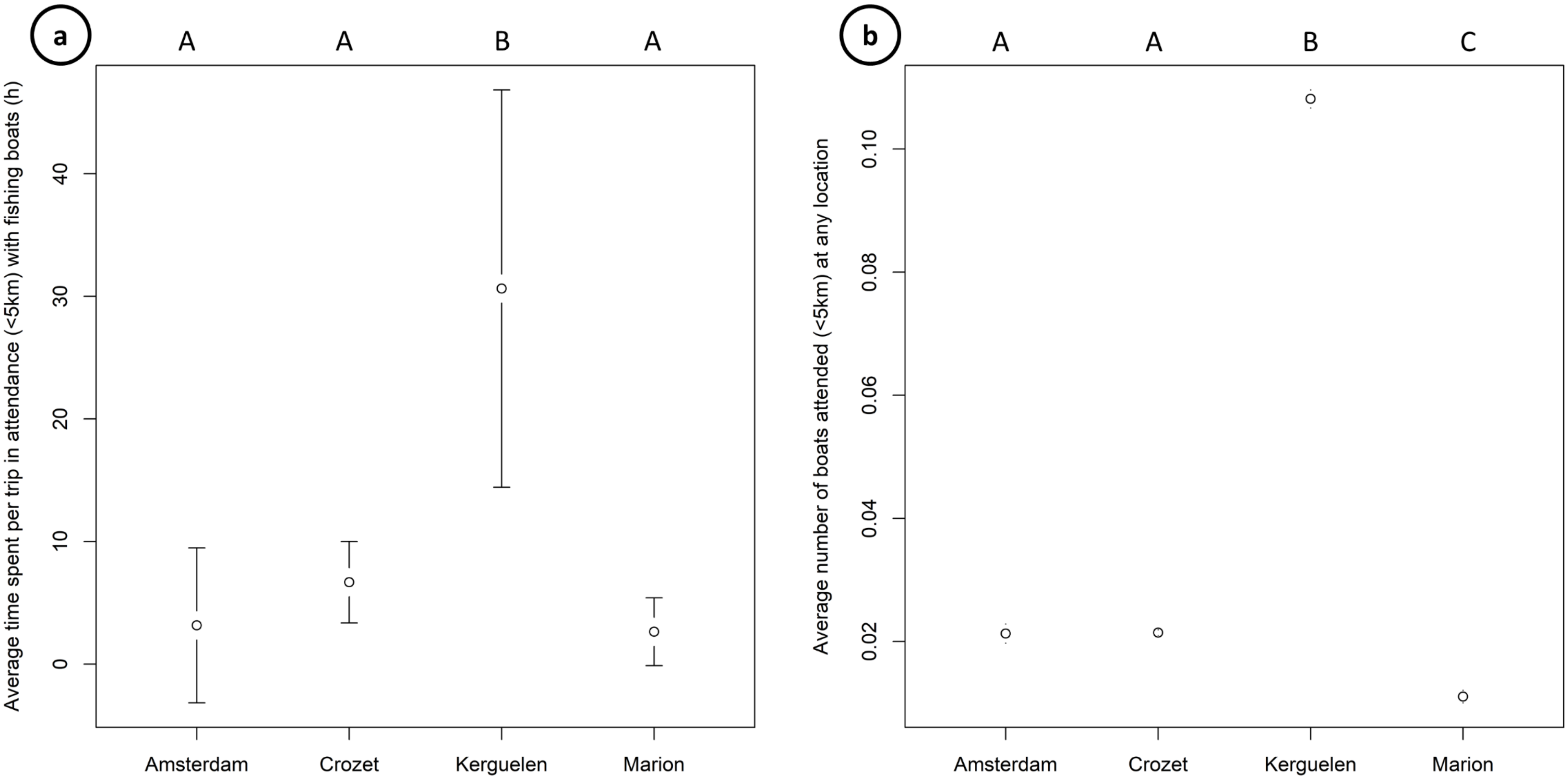
a
A
A
B
A
Average time spent per trip in attendance (<5km) with fishing boats (h)
0
10
20
30
40
Amsterdam
Crozet
Kerguelen
Marion
b
A
A
B
C
Average number of boats attended (<5km) at any location
0.02
0.04
0.06
0.08
0.10
Amsterdam
Crozet
Kerguelen
Marion

Figure 2