

Albatrosses redirect flight towards vessels at the limit of their visual range

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ABSTRACT: Seabird–fishery interactions are important to seabird ecology and conservation since some species obtain a significant amount of food from fisheries, but mortality from bycatch is a primary cause of population declines in several species. While the availability of high resolution GPS data for both seabirds and vessels over the past few years has allowed analyses of fine-scale behavioural responses of seabirds near fishing vessels, little information is available on the distance at which seabirds respond to vessels. Indeed, previous studies have focused on the foraging behaviour of individuals within the vicinity of vessels but have not considered the approach phase of birds. Here we provide such an estimate by examining changes in the flight direction of GPS-tracked wandering albatrosses breeding on the Crozet Islands in response to the toothfish fishing fleet operating around the breeding grounds, monitored using GPS vessel monitoring system data. We show that although we detect increases in feeding behaviour only when albatrosses are within 3 km of boats, they display clear changes in flight direction, towards vessels, at distances up to 30 km. This distance is nearly 3 times as large as previous estimates, almost reaching the theoretical maximum visual range of an albatross. We discuss these results in the light of previous estimates, and pinpoint factors likely to affect the attraction distance. We suggest that this simple estimate of attraction distance could be investigated in other seabird–fishery systems, to improve our understanding of the factors affecting seabird interaction behaviour, and thus better predict when overlap will lead to interactions.

KEY WORDS: Wandering albatrosses · Fisheries · Attraction distance · Foraging behaviour · GPS · Vessel monitoring system · VMS · Crozet · Visual range

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INTRODUCTION

A large number of seabird species associate with fishing vessels, to access abundant and easy food, sometimes representing a substantial part of their diet (Garthe et al. 1996, Arcos & Oro 2002, Arata & Xavier 2003, Colabuono & Vooren 2007, Bugoni et al. 2010, Tew Kai et al. 2013). These interactions, however, present severe conservation issues (e.g. Oro et al. 1996, Votier et al. 2004, Grémillet et al. 2008, Bertrand et al. 2012), in particular because they are linked with accidental mortality through bycatch

(e.g. Brothers et al. 1999, Tuck et al. 2003, Anderson et al. 2011), which is one of the primary threats to seabird populations worldwide (Croxall et al. 2012).

To determine whether birds are likely to interact with fisheries, the probability of encountering fishing vessels is generally estimated by comparing the overlap between the distributions of foraging birds with those of fisheries activities (e.g. Nel et al. 2002, Pichegru et al. 2009, Reid et al. 2013). These proxies can in turn be used to more accurately model the impact of bycatch on population dynamics (e.g. Tuck et al. 2001). However, overlap does not necessarily

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equate to interaction, nor to bycatch. Hence it appears essential to understand when overlap will lead to interaction, and for that purpose, a crucial parameter to take into account is the distance around vessels within which these interactions occur. However, very little work has been dedicated to precisely estimating at what distance birds react to and interact with fishing vessels (Ryan & Moloney 1988, Skov & Durinck 2001, Bodey et al. 2014, see also Thiebault et al. 2014), leading authors to rely on relatively arbitrary distances.

Recently, several authors have used simultaneous GPS tracking of seabirds and fishing boats (Vessel Monitoring System data: VMS) to conduct detailed analyses of individual-level behavioural interactions at fine spatial and temporal scales (Votier et al. 2010, 2013, Granadeiro et al. 2011, 2014, Torres et al. 2011, 2013, Bodey et al. 2014). Most authors noted changes in foraging behaviour in relation to the presence of fisheries, but Bodey et al. (2014) were the first to estimate the distance from boats at which individual birds switched to foraging behaviour directly from their data. Based on speed, acceleration and sinuosity, they distinguished 2 behavioural modes (Wakefield et al. 2013, Bodey et al. 2014): 'foraging' (sudden accelerations, or high turning rates and low speed) or 'commuting' (relatively straight trajectory and constant high speed). Using state space models they established that the presence of vessels increased the probability to switch from 'commuting' to 'foraging' at distances up to 11 km from boats. However, while this approach identified changes in behavioural state, it did not attempt to detect shifts in flight direction within a single behavioural state. Indeed, it is likely that seabirds start their approach from a greater distance, flying towards detected vessels ('commuting-like' behaviour) before really engaging in foraging behaviour.

Here we investigate the behavioural interactions of wandering albatrosses *Diomedea exulans* breeding on the Crozet Islands with the longline toothfish fisheries operating in the French Exclusive Economic Zone (EEZ) around Crozet. Wandering albatrosses are known to overlap widely with and to suffer bycatch mortality from fisheries worldwide (Nel et al. 2002, Xavier et al. 2004, Cuthbert et al. 2005, Walker et al. 2006, Otley et al. 2007, Reid et al. 2013), including individuals of this Crozet population (Weimerskirch et al. 1997a, Barbraud et al. 2013). In this study, we look at the distance from vessels at which birds start to switch towards more frequent foraging behaviour ('feeding distance'), but also at the distance at which they start to fly towards vessels. We

thus provide the first estimate of the 'attraction distance': the distance at which seabirds show an approach response to fishing vessels.

MATERIALS AND METHODS

Albatross tracking data

The study was carried out on Ile de la Possession (Crozet Archipelago 46° S, 52° E). A total of 69 incubating adult birds were equipped with GPS tags (igotU mobile technology): 43 in 2011 (from 14 January to 19 March) and 26 in 2012 (from 25 January to 11 March). Birds were caught on their nest and the GPS tags encased in heat shrink tubing were attached onto back feathers using adhesive Tesa tape. During tag attachment or recovery, birds were either restrained on the nest, or removed while the egg was secured, depending on what was most appropriate in each case. The total mass of attached devices (<32 g including the final package) was well under the 3% recommended threshold (Phillips et al. 2003). Birds were caught on the nest before they started a foraging trip for attachment of devices and on their return to the nest for recovery of tags. All GPS tags had a recording frequency of 15 min (for an expected battery life duration of more than 40 d, covering the wide range of incubation trip duration in this species). In total, 72 tracks were recorded (3 birds made 2 successive trips before being recaptured).

Fisheries data

In the Crozet EEZ, the 7 French longliners targeting Patagonian toothfish were the only legally active vessels operating during the study period. They usually alternated their periods of activity so that vessel density in the area rarely exceeded 3 or 4 at any given time. Data on vessel positions (using GPS technology) for each of these boats was obtained from VMS equipment made available by the Terres Australes et Antarctiques Françaises (TAAF) administration. Vessel positions were recorded every hour. In addition, the exact setting and hauling positions with times were available for all longlines from the Pecheker database, hosted at the Muséum National d'Histoire Naturelle in Paris (Gasco 2011, Pruvost et al. 2011, A. Martin & P. Pruvost unpubl. data). We combined VMS data with fisheries activity data to recreate vessel trips with fishing events. We then made a linear interpolation of positions to obtain 1 position every 10 min.

Attraction distance: directed flight towards vessels

We assumed that a bird attracted to a vessel will demonstrate a flight precisely directed towards it. Therefore, for every GPS location for each bird, we considered each of the heading directions towards all surrounding vessels, together with the related distances to the boat. As we estimated boat locations every 10 min, any bird position will fall within 5 min of an estimated position of any vessel, giving a temporal resolution of ‘simultaneous locations’ of ± 5 min.

For each bird position, we considered the difference between the real direction followed by birds (direction from bird position at time t to bird position at time $t + 1$) with the list of all possible directions the bird could have followed to reach 1 of the vessels present in the EEZ (boats positions at time $t \pm 5$ min). These angular differences α (see Fig. 1), between 0 (bird flying towards a boat) and 180° (bird flying away from a boat), should be uniformly distributed between 0 and 180° if seabirds are not reacting to vessels (and assuming boats and vessels are randomly distributed over the same area). However, this value will be near 0° for a bird flying towards a vessel, so that the α distribution will become more 0-skewed at distances where vessels attract birds. We thus looked at how the α distribution changed depending on the distance from vessels to estimate the range of attraction distances. To do so, we computed the proportion of α values $< 10^\circ$ of the direction of a vessel (i.e. probability $\alpha < 10^\circ$), as a function of the distance (by bins of 1 km) from that vessel. We only used in-flight locations for this ratio (location where the calculated speed is $> 10 \text{ km h}^{-1}$, as albatrosses are unable to sustain flight at lower speeds; Weimerskirch et al. 2002) since travelling abilities and visibility of the boats are considerably reduced for birds sitting on the water, and strongly affected by drift and ocean currents. Each ratio point was established from more than 290 bird positions.

The proportion of $\alpha < 10^\circ$ showed a steep decline followed by a more constant shape as a function of distance, with a clear and sudden transition. We thus modelled it with a piecewise linear regression (Toms & Lesperance 2003), which fits a segmented line to the data and estimates the most likely position of the change in slope. This break point was used as the estimate of the attraction distance: it is the threshold beyond which we do not observe more flights directed towards the boats than ‘usual’. This ‘baseline’ value was compared to the random expectations ($10^\circ/180^\circ = 0.056$) under a uniform distribution. The R package segmented (Muggeo 2008) was used to

apply the piecewise linear regressions (we initialised the break point at 1 km, and *a priori* fixed the number of break points to 1). The results were not significantly affected if we used a 5° threshold for α , or if we binned distances every 2 or 5 km.

Feeding distance: switches to very low apparent speed

Albatrosses have to sit on the water to capture their prey. They may also sit on the water behind a fishing vessel when they wait for offal releases. Thus any feeding behaviour will result in increased time spent sitting on the water, possibly interspersed with flight phases remaining over a small profitable spot. These behaviours associated with feeding will thus result in successive positions with very low apparent speed. As albatrosses cannot sustain flight at speeds of $< 10 \text{ km h}^{-1}$ (Weimerskirch et al. 2002), positions where the apparent speed was lower than this threshold were considered to reflect feeding behaviour. To determine the distance from boats at which we observe that birds start to engage in feeding behaviour, we thus looked at the ratio of the number of low speed locations ($< 10 \text{ km h}^{-1}$) offset against the number of high speed locations ($> 10 \text{ km h}^{-1}$), in relation to the distance from boats (in bins of 0.5 km). We expect this ratio to increase when birds scavenge around vessels. We only considered daylight locations for this ratio. Indeed, at night, wandering albatrosses mainly rest on the sea surface (Weimerskirch et al. 1997b), and thus low speed positions are more likely to reflect resting than feeding, so that including them would possibly weaken the signal. For each distance bin, the ratio was established over > 100 bird positions. As this low/high speeds ratio also showed a steep decline followed by a more constant shape with distance, a piecewise linear regression model was again applied to determine the distance from vessels at which this increase in the ratio began (with 1 break point, initialised at 500 m). Binning distances every 1 km did not qualitatively change the results.

All calculations were conducted in the R environment (R Development Core Team 2012), using routines that we developed.

Effects of GPS sampling regimes and errors in estimated boat position on our results

Both bird and vessel tracks were recorded here with a relatively low frequency compared to the time and

spatial scales at which changes in bird behaviour could occur. Interpolating vessel positions partly overcomes this issue, but introduces some errors in estimated vessel locations. However, we argue here that this is unlikely to affect the conclusions of our study.

A first argument is that by taking a 10° threshold for analysing the α distribution, we overcome the potential lack of sensitivity caused by vessel location uncertainty in the axis perpendicular to the bird direction. At a distance of 30 km, a 10° arc covers a field more than 5 km long (2.5 km long at 15 km), which we estimate to cover the magnitude of potential error in vessel position. Indeed, to have a quantitative idea of the magnitude of errors created by interpolation, we compared the interpolated tracks with inserted fishing events that we used in our analyses to tracks likewise interpolated every 10 min, but without inserting fishing events. The distance between simultaneous estimated locations of the same boats obtained by the 2 different methods was lower than 3 km in 95% of cases (max. 12 km, 70% less than 1 km; see also estimates of errors in interpolation of trawler VMS data by Granadeiro et al. 2011).

However, it could be objected that these small but non-negligible errors in boat positions are potentially causing inaccurate measurements of bird–vessel distances and directions. Our second argument, based on the assumption that errors in boat locations are independent of birds' locations, is that these errors are averaged out to a null value by our statistical treatment. As stated above, each ratio point used in

our analyses (and illustrated in our 2 figures) is established over some hundreds of bird–vessel location couples. The apparent distances are *a priori* equally likely to be over or underestimated relative to the real bird–vessel distance, so that on average, our points should truly represent the distance bin into which they fall. Moreover, these ratio points are not themselves analysed, but used to reveal a general trend with distance, through regression. A similar reasoning applies to inaccurate measurements of apparent directions.

Finally, because we calculate bird direction *a posteriori* by looking at its next position, there remains a possibility that a flight directed towards a boat at an apparent large distance would have actually started only at a closer distance. This is a limit of the bird track sampling regime. However, we again believe that the statistical treatment will largely compensate for this overestimation risk. Having more frequent bird GPS positions might ascertain this, but at least in the case of albatrosses, it could also complicate the analyses because, depending on wind strength and direction, goal-directed flight might not look as straight at lower spatio-temporal scales.

RESULTS

Attraction distance

The proportion of bird positions directed towards boats presented a steep decline followed by a more

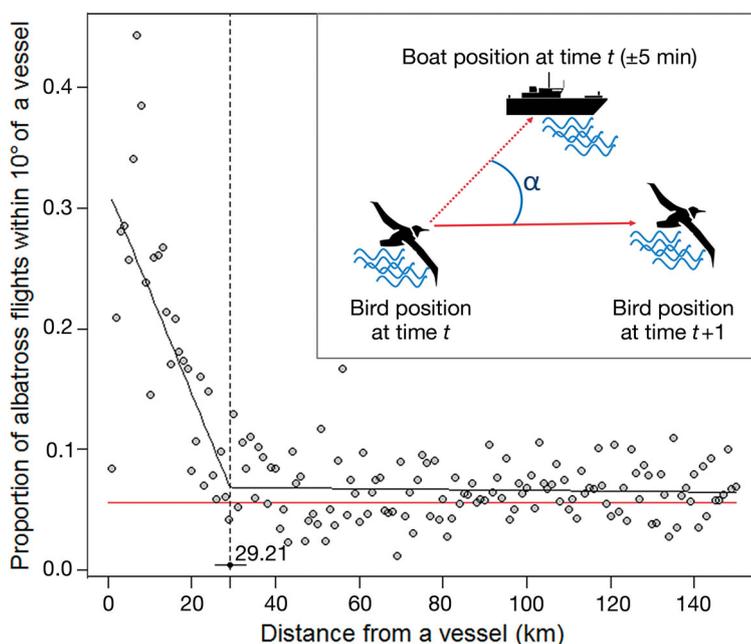


Fig. 1. The proportion of bird movements directed to within 10° of a vessel location. α measures the angular difference between the actual bearing followed by a bird at time t (to reach the location at time $t + 1$) and the hypothetical bearing it should have followed to reach the boat location (at the same moment t). The y-axis shows the probability that $\alpha < 10^\circ$, as a function of the distance from vessels. Each point is a ratio established over all positions falling into the corresponding distance bin (>290 positions to calculate each point). This is used to estimate the 'attraction distance' of albatrosses to vessels. This proportion is modelled by a 2-part piecewise linear regression (—). The proportion (—) expected from a uniform distribution ($10^\circ/180^\circ = 0.056$) that suggests random movement and (---) the breaking value of the piecewise regression at 29.2 km (95% CI: 25.5 to 32.9 km) are indicated. $N = 72$ tracks (69 individuals)

constant shape with increasing distance from boats (Fig. 1). The break point between these 2 phases, which we use as an estimate of the attraction distance, was 29.2 km (95 % CI: 25.5 to 32.9 km).

At distances larger than this threshold, birds did not show any sign of attraction to boats: the proportion of in-flight positions directed towards boats was very close to the value expected under a uniform angular distribution ($10^\circ/180^\circ = 0.056$, Fig. 1), suggesting random directions with respect to vessel locations outside of this range.

Feeding distance

The ratio of low versus high apparent speed positions steeply declined with distance from vessels, up to a threshold of 3.1 km (95% CI: 2.9 to 3.2 km), which we use as an estimate of the feeding distance (Fig. 2). Beyond this threshold distance, the ratio of low versus high apparent speed positions was relatively constant.

DISCUSSION

We propose here a new method to estimate the attraction distance of seabirds to fishing boats. This method specifically considers the phase during which birds are approaching vessels, which had to our knowledge never been precisely quantified (Ryan & Moloney 1988, Skov & Durinck 2001, Spear et al. 2004, Bodey et al. 2014). Wandering albatrosses were shown to be attracted to the Crozet fishing fleet

from distances up to 30 km, while they started to display feeding behaviour only at much closer distances (3 km). This highlights the importance of taking this approach phase into account when considering behavioural reactions of seabirds to vessels, as previous estimates of 'reaction distances' (using various definitions or methodology) were generally of the order of magnitude of 10 km (Wahl & Heinemann 1979, Ryan & Moloney 1988, Skov & Durinck 2001, Bodey et al. 2014).

The attraction distance is likely to vary across different seabird–fishery systems. It could depend on a number of factors, such as the relative quality and quantity of resources available to birds at vessels (themselves linked to fishery type, boat and bird densities, 'natural' prey availability, etc.; Bartumeus et al. 2010, Tew Kai et al. 2013), flight energetics (albatrosses fly at virtually no cost, and might thus more easily afford large distance attractions) or detection capacities. It would thus be of great interest to investigate it in other systems in order to determine which factors are more influential, or how plastic this behavioural response is. It could also be useful in theory to help assess the bias in ship-based seabird counts for estimating seabird densities (Hyrenbach 2001, Spear et al. 2004).

Our attraction distance estimate is that of a maximum attraction distance, with actually few birds reacting to vessels at 30 km (Fig. 1). It can also be used as an estimate of the minimum detection distance capacity: our results indicate that some individual albatrosses seemed to be able to detect boats as far away as 30 km. This value is close to the theoretical distance (32 km; Thiebault et al. 2014) at which

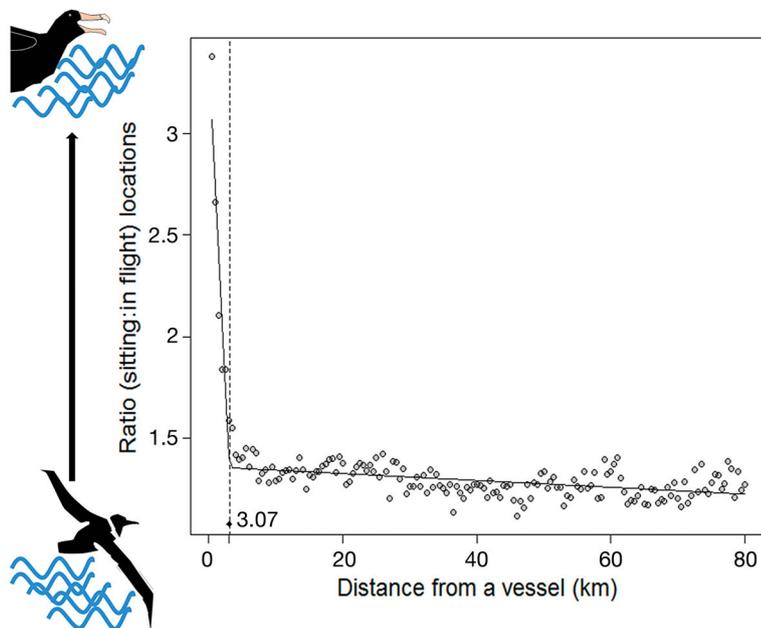


Fig. 2. The ratio of the number of locations with low apparent speed ($<10 \text{ km h}^{-1}$, indicative of sitting and thus feeding) divided by the number of locations with high apparent speed ($>10 \text{ km h}^{-1}$, indicative of travelling flight) in relation to distance from vessels is used to estimate the 'feeding distance' of albatrosses. Each point in the graph is established over >100 bird–vessel relative positions that fall into the corresponding distance bin. This ratio is modelled as a function of distance by a 2-part piecewise linear regression (—). The breaking value of the piecewise regression (---) at 3.1 km (95% CI: 2.9 to 3.2 km) is indicated. $N = 72$ tracks (69 individuals)

fishing boats (approximately 15 m high above the sea here, possibly with aggregations of feeding birds flying around) would fall below the horizon for the eye of an albatross, which flies below 20 m from the sea surface (Tickell 2000). This suggests that vision could play a central role in this species for interactions with boats. Wandering albatrosses are thought to rely on olfaction to catch some of their prey (Nevitt et al. 2008, Mardon et al. 2010), but scent experiments also suggest that, in contrast to a number of other seabird species, they are not attracted by the odour of dimethyl sulphide produced at fisheries (Lequette et al. 1989, Nevitt et al. 1995). It would suggest that detection capacities could sometimes be a limiting factor in the attraction of albatrosses or other seabirds to vessels, which would indicate a high attractiveness of these boats.

This study highlights the relative complexity of behavioural responses of seabirds to fisheries, made available to investigation by GPS tracking data. We urge others to investigate these behavioural reactions in different seabird–fishery systems, to better understand the factors modulating behavioural responses. This will ultimately help policymakers to adopt more accurate and efficient measures to conciliate seabird conservation with fishery practices, by more accurately assessing risks of interactions from overlap information.

Acknowledgements. We are grateful to the administrators of the Pecheker database for making fisheries data available (Alexis Martin, Patrice Pruvost, Nicolas Gasco and Charlotte Chazeau). The Institut Polaire Français Paul Emile Victor (IPEV, programme 109) and the Terres Australes and Antarctique Françaises (TAAF) provided logistical support. We thank Paul Tixier for insightful discussions about fishing operations and vessels, Mark Jessopp for helpful comments during the preparation of the manuscript, and 4 reviewers for their constructive remarks which greatly helped to improve the paper. This work would not have been possible without the contribution of all the fieldworkers of programme 109.

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