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Immersion patterns alone can predict vessel following by albatrosses

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SUMMARY

1. Many pelagic seabird species are threatened by bycatch in fisheries. Bycatch risk assessments benefit from quantifying the frequency, duration and location of individual seabird interactions with fishing vessels. However, proximity-based interaction analyses are limited by the availability and spatiotemporal resolution of bird and vessel tracking data.
2. Here, we examined whether patterns in seabird landing and take-off behaviour (immersion) derived from GLS-immersion loggers (0.167 Hz) can detect vessel interactions when tracking data are lacking or incomplete. We identified close-proximity seabird-vessel interactions by spatiotemporally matching high-resolution GPS data (0.02–1 Hz) from 45 black-browed albatrosses (*Thalassarche melanophris*) to Automatic Identification System (AIS) data from trawler vessels. We used random forest models to investigate whether immersion patterns alone could distinguish these vessel interactions from natural foraging behaviours.
3. We observed multiple seabird-vessel interaction types, with active vessel ‘following’ (with multiple landings) comprising only 59% of discrete interaction events. Other interaction types included ‘stopping’ (with 1 landing) and ‘passing’ (with 0 landings).
4. Using immersion patterns alone, we could distinguish vessel following in >80% of both foraging timesteps and discrete foraging bouts, with false positive vessel following detections totalling <10% of true positives.
5. We found that GLS-immersion loggers sometimes remain wet following take-off, leading to inflated durations of on-water periods. However, leaving this error uncorrected only slightly reduced the performance of our random forest models.
6. *Policy implications.* We demonstrate that seabird immersion patterns alone can detect high-risk seabird-vessel interactions, even in the absence of locational data for both seabirds and vessels. Our approach could allow for more comprehensive seabird bycatch risk assessments that quantify previously hidden seabird-vessel interactions, such as those involving migratory life history stages and illegal, unreported or unregulated (IUU) fishing vessels.

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Supporting information

(Including R scripts and detailed information on GLS-immersion error)

<https://besjournals.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2F1365-2664.70085&file=jpe70085-sup-0001-FigureS1-S17-TableS1-S3.pdf>

Data and scripts

<https://github.com/jonathanrutter8/immersion-patterns>

RESEARCH ARTICLE

Immersion patterns alone can predict vessel following by albatrosses

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KEYWORDS

AIS, bycatch, immersion, IUU, random forest, seabird behaviour, seabird-fishery interactions

1 | INTRODUCTION

Many pelagic seabird species are threatened by incidental mortality (bycatch) in commercial fisheries (Dias et al., 2019). Bycatch mainly occurs when seabirds attracted to vessels by foraging opportunities are caught, entangled or struck by fishing gear (Melvin et al., 2023). Data on global bycatch rates, where available, suggest that annual individual mortalities number at least 160,000 in long-line fisheries (Anderson et al., 2011) and 44,000 in trawl fisheries (Phillips et al., 2024). Low fisheries observer coverage and widespread cryptic (unobservable) mortality mean that these mortality rates are inevitably underestimated (Anderson et al., 2011; Ewell et al., 2020; Phillips et al., 2024). Especially where observer data are scarce, spatiotemporal analyses of seabird-fishery overlap are critical to assess where and when bycatch risk is highest to inform mitigation strategies (Good et al., 2020; Small et al., 2013). However, robust overlap analyses require high-resolution tracking data, which is often lacking for certain fisheries and seabird life history stages (Votier et al., 2023). A new approach to predicting fine-scale seabird-vessel interactions, without the use of high-resolution tracking data, could therefore represent a major advancement for bycatch risk assessment.

Concurrent tracking of seabirds and fisheries is often used to identify areas and periods of bycatch risk exposure (Le Bot et al., 2018). When bird and vessel tracking data are collected with sufficiently high spatiotemporal resolution, it is possible to detect discrete events in which an individual bird approaches a vessel within a certain spatiotemporal proximity (Carneiro, Clark, et al., 2022; Rutter et al., 2024). Quantifying these finer-scale interactions (also called attendances, associations or visits) can reveal how bycatch risk varies among individual birds and vessels (Corbeau, Collet, Orgeret, et al., 2021; Roberson & Wilcox, 2022; Torres et al., 2013). However, high-resolution tracking data are difficult to collect for juvenile and non-breeding seabirds that spend long periods at sea, potentially biasing estimates of bycatch risk (Carneiro et al., 2020; Gianuca et al., 2017). Vessel tracking data are also limited. Three-quarters of industrial vessels worldwide do not have publicly available Automatic Identification System (AIS) or Vessel Monitoring System (VMS) data (Paolo et al., 2024), and some vessels (legally or illegally) disable AIS during some activities (Welch et al., 2022). Furthermore, a substantial portion of the world's fishing effort is expended by near-shore or small-scale fleets lacking AIS (Rousseau et al., 2024). These 'unseen' fishing vessels may have high levels of seabird bycatch, yet their impacts on populations are uncertain and potentially underestimated (Araújo et al., 2022; Weimerskirch et al., 2020; Welch et al., 2024). The difficulty of detecting seabird interactions with unseen fishing vessels has motivated the development of several tracking-based

solutions. Bird-borne cameras can provide visual confirmation of vessel attendance but are also heavy and short-lived (Clark et al., 2022; Votier et al., 2013). Light-level geolocators (GLS) can detect light from nearby fishing vessels but only at night (Darby et al., 2023; Dupuis et al., 2021). Some GPS tags can detect vessel radar within 5 km, but these devices detect nearby vessels less than half the time (Carneiro, Dias, et al., 2022; Navarro-Herrero et al., 2024; Weimerskirch et al., 2020).

Detecting seabird-vessel interactions from bird behaviour alone would overcome many of the data limitations associated with seabird and vessel tracking. Seabirds may exhibit distinct behaviours when they are attending vessels (Corbeau et al., 2019; Torres et al., 2011; Votier et al., 2010). However, these behaviours depend on feeding ecology and fishery type, and their classification may change depending on data resolution, making it difficult to generalise across the literature. For example, northern gannets tend to fly straighter and faster near vessels (Votier et al., 2010), white-capped albatrosses tend to fly straighter and slower near vessels (Torres et al., 2011) and wandering albatrosses tend to show more tortuous flight near vessels (Corbeau et al., 2019). Several studies show that vessel presence affects the probability of seabirds switching behavioural states (Bodey et al., 2014; Cianchetti-Benedetti et al., 2018; Clark et al., 2020; Collet et al., 2015), but have not determined whether the behaviours themselves are diagnostic of vessel interaction. Even within a single fishing fleet, there may be high variation in interaction rates between similar species (Collet et al., 2017) and among conspecific individuals (Granadeiro et al., 2011; Torres et al., 2011; Votier et al., 2010) and populations (Corbeau, Collet, Pajot, et al., 2021; Granadeiro et al., 2011). Perhaps for all these reasons, no study to our knowledge has successfully found a predictive behavioural signature of seabird-vessel interaction. In particular, Carneiro, Dias, et al. (2022) found that integrating GPS and GLS-immersion data at 10-min resolution was insufficient to predict wandering albatross-vessel interactions as distinct from natural (non-vessel-associated) foraging behaviours.

Here, we devised a solution to the challenge of using behavioural patterns to predict unseen seabird-vessel interactions. To bypass the limitations of both seabird and vessel tracking data, we aimed to identify interactions without the use of spatiotemporal proximity. Instead, we focused our analysis on patterns of landings and take-offs (hereafter, immersion). Using GLS-immersion loggers, we explored how fine-scale immersion patterns differed between natural and vessel-associated foraging by albatrosses at sea. We used high-resolution GPS to identify interactions with AIS-equipped fishing vessels and to verify GLS-derived immersion patterns. We derived several rolling metrics from the immersion data, including a measure of immersion 'regularity' that captured the stereotypical landing and take-off behaviour often displayed

by birds following vessels. Finally, we used random forest models to test whether these immersion metrics alone could accurately predict vessel following behaviour, both over time and in discrete foraging bouts.

2 | MATERIALS AND METHODS

2.1 | Data collection

This study investigated vessel interactions of black-browed albatrosses (*Thalassarche melanophris*) breeding on New Island, Western Falklands. This species is highly attracted to fishing vessels (Collet et al., 2017) and is frequently bycaught through cable strikes and net entanglement in Argentine and Falklands trawlers across the Patagonian shelf (Favero et al., 2011; Kuepfer et al., 2022; Tamini et al., 2015, 2023). We obtained positional and behavioural data by deploying archival GPS and geolocator (GLS) devices during single foraging trips during late incubation and early chick rearing (10–31 December 2017; see Guilford et al., 2022 for more details on deployments). We used Tesa tape to attach back-mounted GPS to 45 birds, and metal rings to attach leg-mounted GLS equipped with saltwater immersion loggers to 42 of those birds. GPS loggers (prototype Mobile Action IgotU modified to include a larger battery) were programmed to record 1 positional fix every 1 s ($n = 5$), 5 s ($n = 25$), 10 s ($n = 11$) or 1 min ($n = 4$) to test their lifespan across a range of temporal resolutions. GLS-immersion loggers (Migrate Technology Intigeo-C65) were programmed to sample their immersion state (wet/dry) once every 6 s and record every change in state (Mode 8). The combined weight of these loggers and other devices whose data were not analysed here did not exceed 40 g (<1.5% body mass). Fieldwork was carried out under Research Licence No: R29/2017 granted by the Environmental Planning Department of the Falkland Islands Government. At the time, no approval from an animal ethics committee was required for this kind of work.

We obtained tracks of vessels near tracked birds from AIS data processed by Global Fishing Watch (GFW). AIS data consist of vessel locations and public vessel registries, which GFW analyses to predict active fishing (accuracy >90%; Kroodsmas et al., 2018). We queried AIS data for all vessels (including non-fishing-type vessels) within 50 km and 1 h. of each bird position, down-sampled to 1 bird position every 10 min. Vessels analysed in this study were predominantly located in the Argentine Exclusive Economic Zone (EEZ), with some non-fishing-type vessels located in the Falklands EEZ. High-quality AIS is used by >80% of large vessels in both EEZs (Arrizabalaga et al., 2019). Furthermore, there are relatively few small vessels (<12 m) in the Argentine fleet, and almost none in the Falklands fleet (Arrizabalaga et al., 2019). A relatively modest amount of fishing by untracked industrial vessels has been detected in these waters (Paolo et al., 2024; Welch et al., 2022). Thus, we assume our dataset of vessel tracks is reasonably, though not perfectly, comprehensive.

Data processing and all subsequent analyses (Sections 2.2–2.5) were performed using R 4.4.1 (R Core Team, 2024). R scripts are available in [Supporting Information S1](#).

2.2 | Immersion correction

Visual inspection of GLS-immersion data in relation to GPS animations (i.e. dynamic track maps created using the R package *gganimate*; Pedersen & Robinson, 2024) revealed inconsistencies between movement and immersion in several individual bird tracks. GLS-immersion loggers often recorded 'wet' when a bird was obviously flying, meaning the logger should have been 'dry'. This error tended to occur immediately following a take-off, visible in animations as a sudden increase in speed. Understanding this error was essential to subsequent analyses (Sections 2.3–2.5), which relied on accurate fine-scale measurements of wet and dry period duration. To quantify and correct this error, we used Hidden Markov Models (HMMs) to derive wet and dry behavioural states (i.e. sitting on the water and flying) from GPS data using the R package *momentuHMM* (McClintock & Michelot, 2018). We then integrated the resulting HMM-immersion sequences with our original GLS-immersion sequences to produce a final corrected dataset with immersion states at 6-s intervals (see [Supporting Information S2](#) for full details on HMM-based immersion correction).

2.3 | Detection and classification of bird-vessel interactions

We detected interactions of individual birds and vessels by overlapping their GPS/AIS tracks in space and time. We defined a bird-vessel interaction as the co-occurrence of a bird fix and a linearly interpolated vessel position at the same time within 1 km. We produced static and animated track maps for each discrete interaction event to allow for close visual inspection of bird behaviour, including immersion near vessels. Vessel identifying information, including flag state, vessel type, fishing gear type and fishing activity (fishing or not), was also collected for each interaction.

Analysis of maps and animations revealed three distinct types of interaction, which we classified manually as follows: *Following* behaviour was characterised by close tracking of a moving vessel (within ~100 m) and a series of (at least 2) water landings. *Stopping* behaviour involved a single landing at a vessel, with no subsequent take-off to catch up to the vessel as it moved away. Finally, *passing* behaviour had no associated landings; the bird approached the vessel within the 1 km threshold but remained in flight. We ignored any interactions in which a bird was near a non-fishing-type vessel (e.g. a passenger ferry). For our remaining analyses, we chose to focus only on vessel *following* interactions for two reasons. First, we assumed vessel interactions with 0–1 landings would be indistinguishable from non-vessel-associated behaviours using immersion data alone. Second, we assumed following of fishing vessels

poses higher bycatch risk than other interactions, as most bycatch of black-browed albatrosses occurs on the water very close to the vessel stern (Kuepfer et al., 2022; Tamini et al., 2023). We defined the start and end times of following events as the estimated time (to the nearest minute) of the start of the first wet period, and end of the last dry period (if before an extended wet period) or wet period (if before an extended dry period). Occasionally, animations and maps showed recognisable vessel following behaviour continuing beyond the bounds of the original 1 km threshold. These cases, when associated with large gaps in vessel AIS positions, were assumed to constitute part of the same following event.

2.4 | Derivation of immersion metrics

Animations of bird-vessel interactions revealed periodic behaviour patterns during vessel following. Birds often landed behind a moving vessel, took off shortly afterwards to catch up to it and repeated the process several times at regular intervals. To quantify these landing and take-off patterns, we calculated 5 metrics from a rolling window across the 6-s interval immersion data: mean wet period duration, mean dry period duration, proportion wet, number of landings and immersion regularity. Immersion regularity was a custom metric (range 0–1) developed to capture the periodicity of landings and take-offs in a rolling window, with higher values representing more consistent durations of wet and dry periods (Supporting Information S3.1). We calculated these metrics separately for the corrected and uncorrected datasets (Section 2.2). We defined rolling window size for all metrics based on a preliminary analysis of the ability of immersion regularity to predict vessel following across a range of window sizes (Supporting Information S3.2). We then truncated our dataset to foraging periods, defined as timesteps where the 'proportion wet' metric was >0 or <1 (i.e. removing sustained resting and flying periods; Fayet et al., 2016). Thus, our subsequent analyses sought to distinguish between two types of foraging: vessel following and 'natural foraging' (which could also include stopping and passing near vessels).

2.5 | Predictive modelling

We employed a supervised machine learning approach to test whether vessel following could be predicted using immersion data alone. Our response variable was binary (following or natural foraging), highly imbalanced (following occurred in ~1.2% of foraging timesteps) and temporally autocorrelated within individuals. We anticipated that our predictors, all rolling metrics derived from immersion data, would have nonlinear relationships with each other and our response variable. To account for this complexity, we fitted random forest models using the R package *caret* (Kuhn et al., 2020). For all models, we fitted 500 trees per fold with the number of features considered at each decision tree split (*mtry*) set to the square root of the number of predictors (rounded down; Liaw & Wiener, 2002).

We fitted 8 random forest models in total, representing 2 variations each of data type, immersion correction and predictors (see Table 1 in Results). First, recognising that bird-vessel interactions can be quantified both in terms of duration and number of interactions (Carneiro, Clark, et al., 2022; Rutter et al., 2024), data type could be either 'time-based' or 'bout-based'. For time-based models, each observation of the dataset represented a single 6-s foraging timestep; for bout-based models, each observation represented a discrete foraging bout containing any number of timesteps. Thus, each foraging bout was separated from the next by at least 1 rolling window-length of continuous sitting (wet) or flying (dry). We recalculated bout-based immersion metrics so that they reflected the duration of the bout, rather than a rolling window. The immersion regularity metric was an exception, as we calculated the maximum rolling regularity value for each bout. Second, immersion correction could be either 'corrected' or 'uncorrected' (Section 2.2). Finally, predictors could consist of either immersion regularity alone, or all five predictors (regularity, mean wet duration, mean dry duration, proportion of time spent wet, number of landings). See Supporting Information S4 for further details on these models.

We assessed model performance through fivefold cross validation. Our focal metrics of model performance were sensitivity (proportion of true positives) and false positive ratio (FP ratio; the ratio of false positives to known positives). FP ratio was a more intuitive measure of false positive prediction than specificity, precision or accuracy given the class imbalance of our dataset (low prevalence of vessel following). We considered a model to be predictive if it had (1) $>75\%$ sensitivity (following Carneiro, Dias, et al., 2022) and (2) $<10\%$ FP ratio (i.e. relatively few false positives).

3 | RESULTS

3.1 | Foraging trip characteristics

We successfully retrieved GPS devices after single trips from all 45 tagged albatrosses, 42 of which were also equipped with immersion loggers. Foraging trips lasted between 0.4 and 5.2 days (mean 1.9 days), although the GPS tracks from 11 of these trips were cut short when the battery died. Most birds flew towards the southern Patagonian shelf, where they foraged within the Argentine EEZ. Four birds stayed within the Falklands EEZ. We describe vessel-associated behavioural patterns during these foraging trips in Sections 3.3–3.4.

3.2 | Immersion correction

GLS-immersion data were often inconsistent with HMM-derived immersion data, hence our decision to correct the data (Supporting Information S2). We found that 12.6% of timesteps recorded as wet by GLS were incorrect as birds were in flight (dry). This error appeared in $>5\%$ of GLS wet timesteps in 63.2% of devices. Most of this error was due to GLS staying wet for an average of 31.6 s (but

up to 33 min) after take-off. Upon visual inspection, corrected immersion data were far more consistent with animated GPS tracks.

3.3 | Bird-vessel interactions

When we overlaid bird GPS data with vessel AIS data (fix intervals mean 5.1 min, range 0.03–3146.1, SD 38.4), we found that 13 birds (29%) flew within 1 km of at least 1 fishing vessel during their single tracked foraging trip (Supporting Information S5). Eight individuals approached vessels multiple times in a single trip (up to 8 discrete interactions), while 5 individuals only had a single interaction. Using animations, we identified 23 *following* events (59%), 8 *stopping* events (21%) and 8 *passing* events (21%) for a total of 39 interactions (Figure 1; Supporting Information S5). Five (22%) following events occurred at night (between 22:05 sunset and 04:45 sunrise local time). All following events occurred on the southern Patagonian Shelf with 3 specific Argentina-flagged freezer trawler vessels. On average, following events lasted 19.4 min (range 4.0–56.0, SD 14.9) between a bird's first landing behind a vessel and its final landing or take-off.

3.4 | Immersion metrics

Animations and maps showed that many vessel-following events were characterised by highly regular immersion patterns. During these events, birds would rapidly home in on a vessel, land on the water for an average of $1.3 \pm \text{SD } 1.2$ min, fly to catch up to the receding vessel for $0.8 \pm \text{SD } 0.7$ min and repeat this process $4.7 \pm \text{SD } 2.0$ times (means and SDs calculated within a 12-min rolling window). High-resolution (GPS ≤ 10 s) flight paths between wet periods took many shapes, from straight paths to complete loops, even as the general direction of movement matched that of the vessel (Figure 2a). Our custom immersion regularity metric successfully matched with these visibly regular periods of vessel following (Figure 2b,c; Supporting Information S6.1). We chose a 12-min rolling window over which to calculate all immersion metrics (Supporting Information S3.2).

Immersion patterns during vessel following periods appeared distinct from those during natural foraging periods (Figure 3). During vessel following, birds exhibited more landings, higher regularity and more consistent wet and dry period durations. These patterns emerged both over continuous time and within discrete bouts.

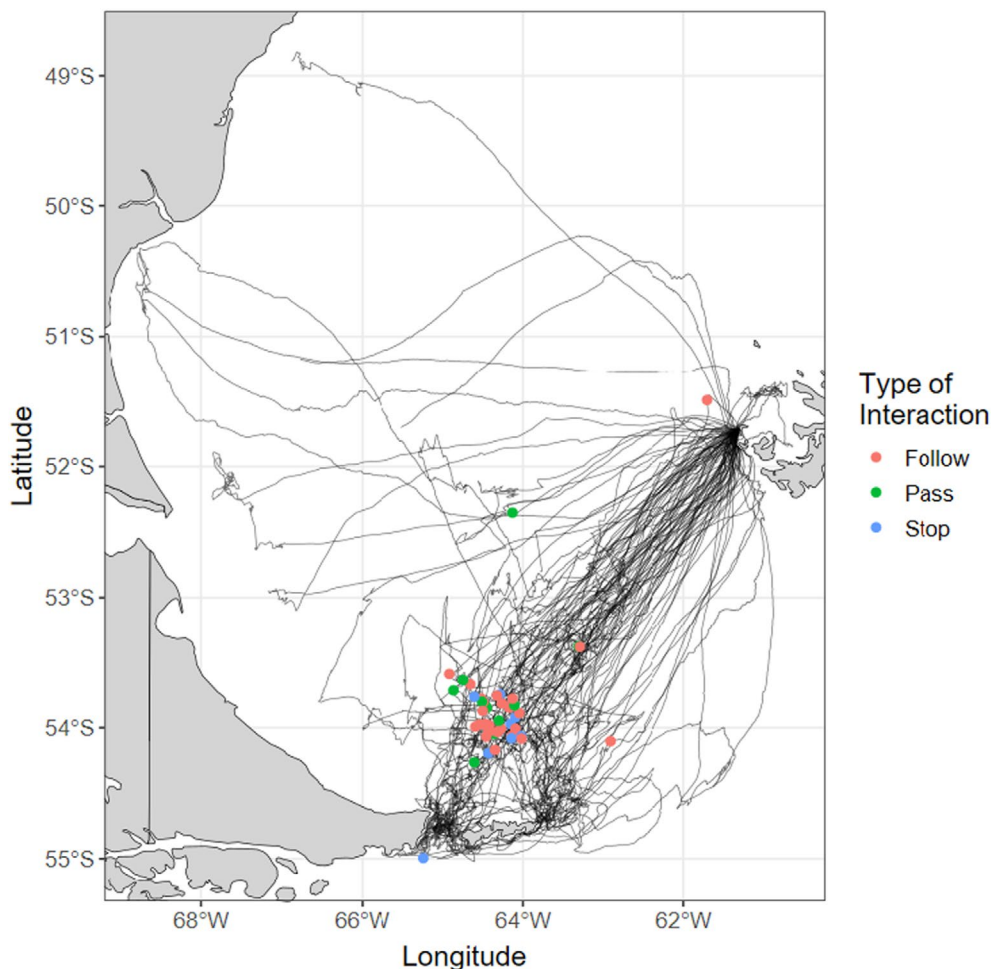


FIGURE 1 GPS tracks of 45 breeding black-browed albatrosses tagged on New Island, Western Falklands, with locations of vessel interactions indicated by type.

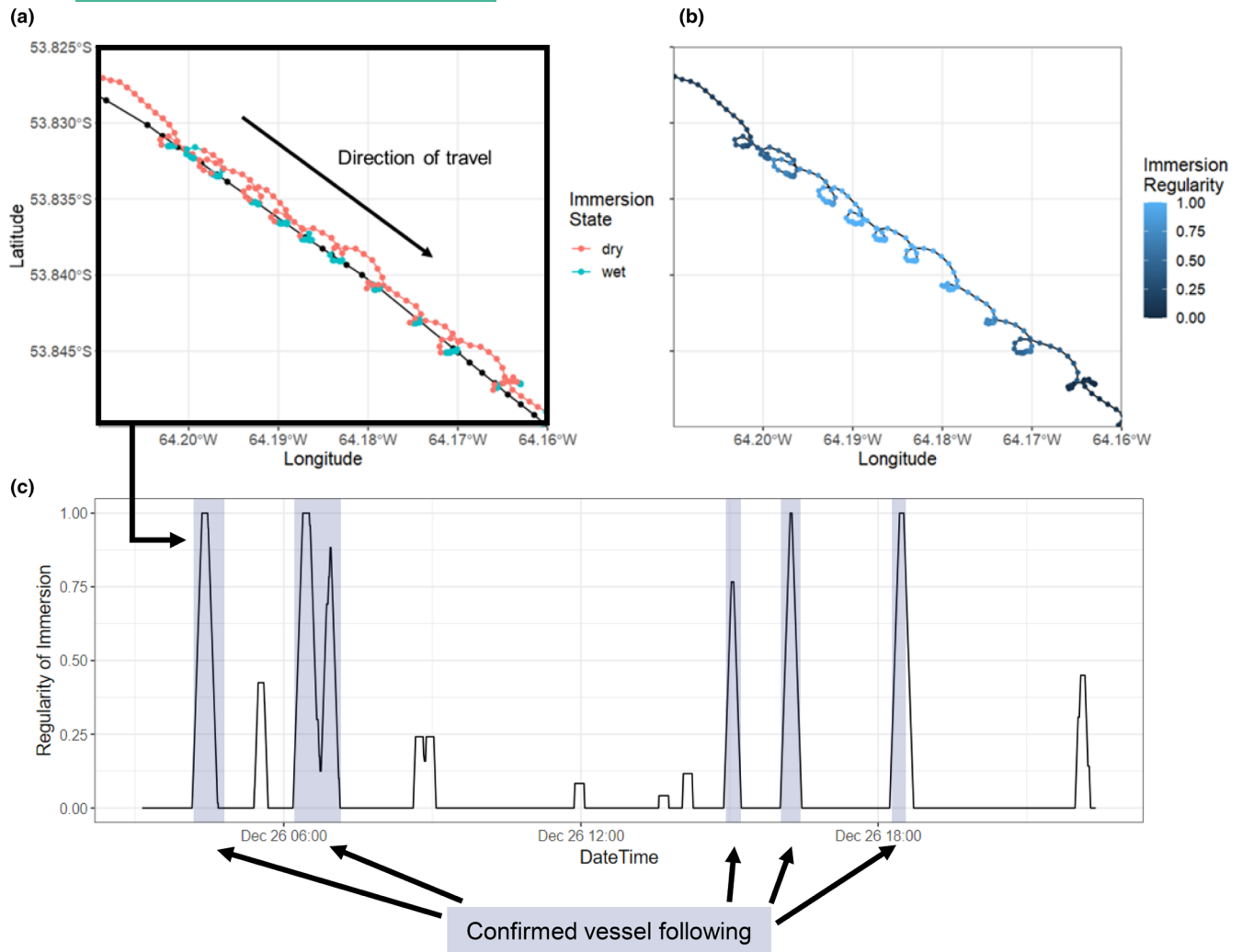


FIGURE 2 (a) Example of a segment of track (bird 75F red) during a vessel following event (vessel track with AIS fixes shown in black). Bird movement and uncorrected immersion patterns appear regular. See [Supporting Information S5](#) for animations of vessel interactions. (b) Immersion regularity metric overlaid on the same segment of track. (c) Time series of immersion regularity for the same bird, overlaid with periods of confirmed vessel following. Highly regular periods align reliably with vessel following periods. The first vessel following period in this time series is the same one shown spatially in (a).

3.5 | Prediction of vessel following

We successfully predicted vessel following from immersion data using random forest models (Table 1, [Supporting Information S6](#)). Models with all 5 immersion metrics included as predictors (Models 2, 4, 6 and 8) met our objective of >75% sensitivity and <10% FP ratio. With corrected immersion data, we were able to predict 80.1% of confirmed vessel following time, with false positive predictions lasting only 1.3% of confirmed following time (Model 2). Even with uncorrected immersion data, these performance metrics were only marginally worse (76.8% sensitivity, 1.8% FP ratio; Model 4). We were also able to predict 80% of discrete vessel following bouts, with false positive predictions totalling 10.0% of confirmed following bouts (Model 6). Unexpectedly, using uncorrected immersion data slightly improved the performance of the bout-based model (86.7% sensitivity, 0% FP ratio; Model 8). Across all models, the minimum sensitivity and maximum FP ratio did not always meet our objectives, probably

because only 2 birds with confirmed vessel following were included in each cross-validation fold. However, when averaged across folds, these performance metrics met our objectives. All models had specificity >99.5% due to the low prevalence of vessel following (1.2% of foraging timesteps, 1.0% of foraging bouts), hence our use of FP ratio to more easily interpret false positives.

Compared to the models with all predictors, models with immersion regularity as the only predictor (Models 1, 3, 5, 7) did not meet our performance objectives (Table 1). Nevertheless, immersion regularity was still far more important than any other immersion-based metric in predicting vessel following (Figure 4). In contrast, the number of landings was not an important predictor in any of our models, likely because it was closely related to the mean wet and mean dry predictors.

Misclassifications (false negatives and positives) generally occurred during short-duration foraging events with few landings. However, some false positive classifications appeared to reflect true following of vessels without active AIS ([Supporting Information S6](#)).

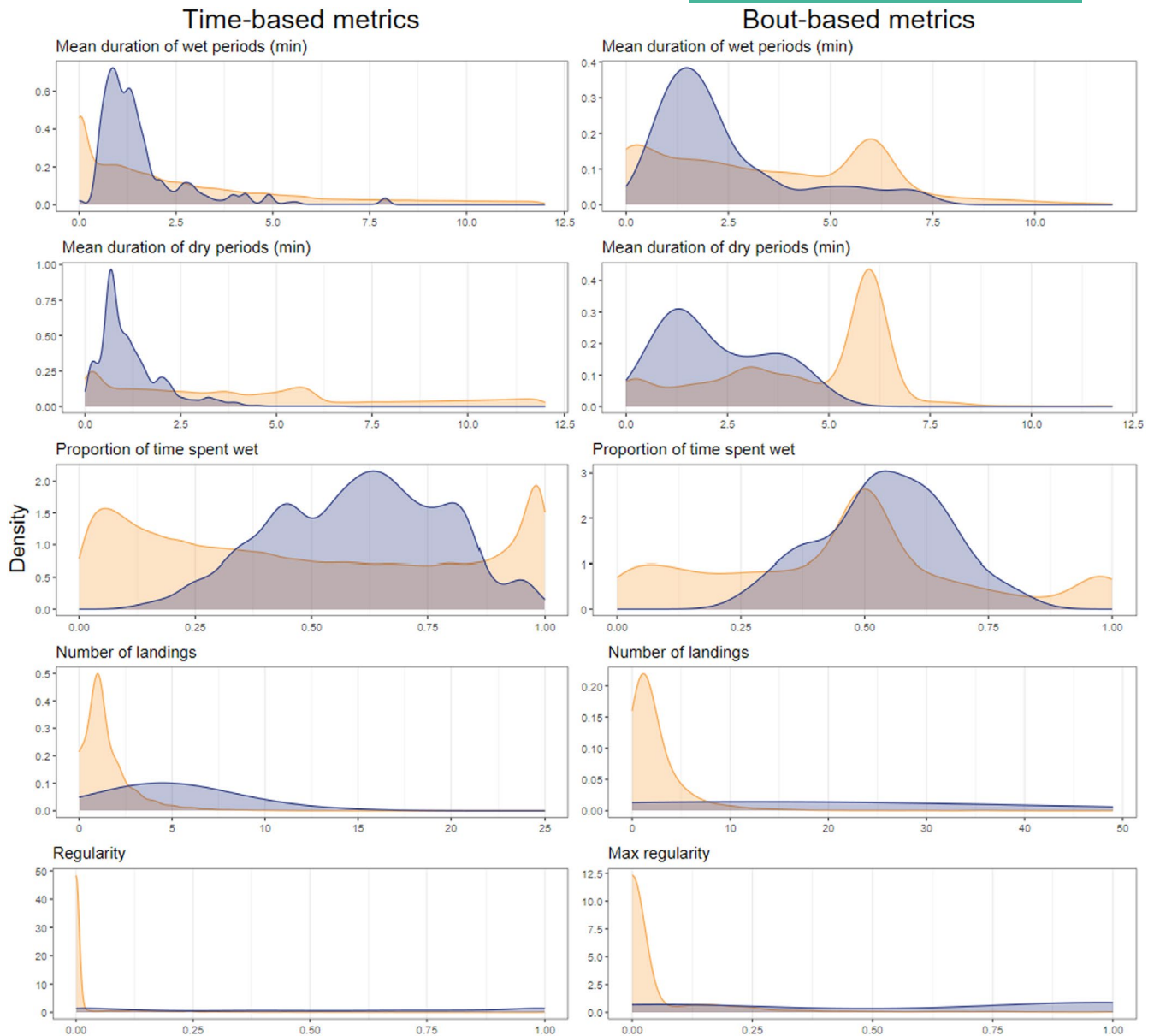


FIGURE 3 Density histograms of immersion metrics for breeding black-browed albatrosses, comparing vessel following (purple) with natural foraging (orange). Time-based metrics (left) were calculated for each bird within a 12-min rolling window at 6-s timesteps. Bout-based metrics (right) were calculated within discrete contiguous foraging periods (bouts). All plots show metrics calculated from corrected immersion data.

4 | DISCUSSION

Using a case study of black-browed albatrosses, we demonstrated that remotely derived seabird behaviour patterns can be used to predict interactions with fishing vessels. Not only are some trawler-associated behaviours distinct from natural foraging behaviours, but this distinction can be made using wet/dry immersion data alone. Our analyses produced 3 key findings: first, there are multiple types of close-proximity seabird-vessel interactions, with active vessel 'following' comprising only 59% of discrete interaction events. Second, immersion patterns alone can distinguish vessel following from natural foraging in >80% of both timesteps and discrete foraging bouts, with an acceptably low proportion of false positive

detections (<10% FP ratio). Third, GLS-immersion devices produce imperfect immersion data, but even without correction, they are still sufficient to predict vessel following.

4.1 | Behavioural variations in seabird-vessel interaction

The black-browed albatross is known to interact with multiple types of fisheries across the Southern Hemisphere (Brothers et al., 2010; Collet et al., 2017; Richard et al., 2020; Tamini et al., 2023). In our study, all vessel interactions were with Argentine freezer trawlers that target hoki, southern blue whiting and Patagonian toothfish along the

TABLE 1 Performance metrics from binary classification random forest models predicting vessel following by black-browed albatrosses.

Model	Data type	Immersion correction	N	Predictors ^a	Sensitivity	FP ratio	Specificity	Accuracy	Kappa	F ^b
1	Time	Corrected	387,760	Regularity	0.224 (0, 0.436)	0.107 (0, 0.2)	0.999 (0.996, 1)	0.991 (0.983, 0.996)	0.305 (-0.002, 0.575)	NaN (NaN, NaN)
2*	Time	Corrected	382,324	All	0.801 (0.395, 0.963)	0.013 (0.001, 0.03)	1 (1, 1)	0.998 (0.994, 0.999)	0.864 (0.561, 0.978)	0.865 (0.563, 0.979)
3	Time	Uncorrected	400,043	Regularity	0.204 (0.029, 0.425)	0.351 (0.003, 1.605)	0.999 (0.994, 1)	0.99 (0.982, 0.995)	0.298 (0.018, 0.565)	0.302 (0.022, 0.568)
4*	Time	Uncorrected	395,033	All	0.768 (0.604, 0.971)	0.018 (0.005, 0.044)	1 (1, 1)	0.997 (0.995, 1)	0.852 (0.741, 0.983)	0.853 (0.742, 0.983)
5	Bout	Corrected	1863	Regularity	0.467 (0, 1)	0.273 (0, 0.5)	0.997 (0.995, 1)	0.992 (0.983, 0.998)	0.44 (-0.005, 0.856)	NaN (NaN, NaN)
6*	Bout	Corrected	1863	All	0.8 (0.5, 1)	0.1 (0, 0.5)	0.999 (0.997, 1)	0.997 (0.993, 1)	0.832 (0.497, 1)	0.833 (0.5, 1)
7	Bout	Uncorrected	1848	Regularity	0.463 (0.25, 0.833)	0.34 (0, 1)	0.997 (0.994, 1)	0.992 (0.987, 0.997)	0.515 (0.281, 0.908)	0.519 (0.286, 0.909)
8*	Bout	Uncorrected	1848	All	0.867 (0.5, 1)	0 (0, 0)	1 (1, 1)	0.999 (0.997, 1)	0.915 (0.665, 1)	0.915 (0.667, 1)

Note: Metrics are reported as the mean (min, max) of the five cross-validation folds. Models with an asterisk (*) met our objective of >75% sensitivity and <10% FP ratio.

^aAll predictors included immersion regularity, mean duration of wet periods, mean duration of dry periods, proportion of time spent wet and number of landings.

^bThe F statistic was undefined (NaN) when at least one of the five folds had 0 sensitivity.

southern Patagonian Shelf (Tamini et al., 2023). The black-browed albatross regularly feeds on discards (whole fish and offal) from these and other Argentine bottom and mid-water trawlers, resulting in >400 estimated mortalities per year through both cable collisions and net entanglement (Tamini et al., 2023). Bird-scaring lines (BSLs) have been legally required as a bycatch mitigation measure in this fleet since 2017 (the same year we tracked these birds; Consejo Federal Pesquero, 2017). However, as these regulations do not cover all types of trawl cables nor limit discarding, bycatch remains a serious threat at these vessels (Tamini et al., 2023), and bycatch risk assessments are still needed to justify and target further management efforts.

Birds in our study displayed a variety of behavioural patterns in relation to vessels. Similar to previous studies (Granadeiro et al., 2011; Torres et al., 2011; Votier et al., 2010), we found high levels of individual variation in birds' attraction to vessels, with some individuals re-approaching the same vessels multiple times. Less discussed in the literature, though perhaps unsurprising, was our first key finding: at fine spatiotemporal scales, there are multiple types of vessel interactions (following, stopping and passing) that can be characterised by number of landings. Vessel following patterns are consistent with previous observations of black-browed albatross behaviour around trawlers. When trawlers discard fishing waste, albatrosses land near the stern to feed through surface seizing and occasional diving (González-Zevallos & Yorio, 2011), sometimes in aggregations of over 500 individuals (Favero et al., 2011; Kuepfer et al., 2022). Bycatch is most likely to occur during these periods, when birds are on the water within 200m of a trawler's stern (Favero et al., 2011; Kuepfer et al., 2022; Tamini et al., 2023). Birds may still be at risk of cable collisions while passing or stopping at a vessel, but they likely spend less time exposed to fishing gear, especially if the vessel is not actively discarding waste (Kuepfer et al., 2022). Thus, we suggest that of the different types of vessel interactions we observed in this study, vessel following poses the highest risk of bycatch.

4.2 | Prediction of vessel following using immersion data

We found that immersion patterns alone can reveal vessel following without locational data from birds or vessels. Using random forest models, we detected vessel following time/bouts with high sensitivity (>75%) and specificity (<10% FP ratio). By comparison, Carneiro, Dias, et al. (2022) used random forest models to predict vessel interactions for wandering albatrosses based on several movement and immersion variables, and their models all had 0% sensitivity. Our improved results may be due to our focus on vessel following by the black-browed albatross, rather than all close proximity interactions of the more generalist wandering albatross (Collet et al., 2017). Additionally, our use of higher resolution data (6-s immersion vs. 10-min GPS and summarised immersion) allowed us to derive a more informative set of predictor variables. The most important of these predictors was immersion regularity, which captures the strikingly periodic landing and take-off patterns that we observed during

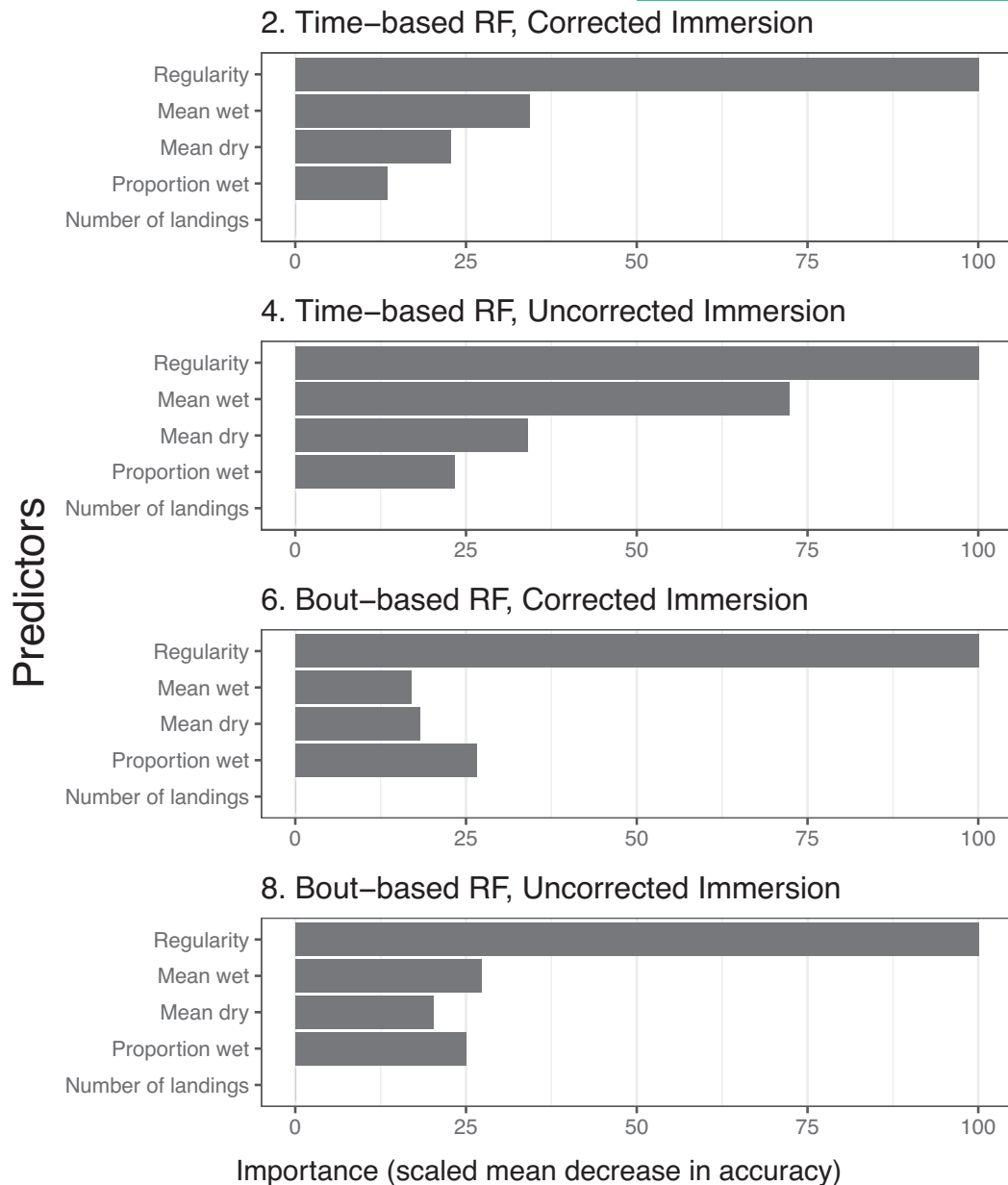


FIGURE 4 Variable importance plots from random forest models predicting vessel following by black-browed albatrosses. Models 2, 4, 6 and 8 are shown as these included all predictors (Table 1).

vessel following. We suggest this regularity may result from trawlers moving at a constant speed while discarding continuously (Kuepfer et al., 2022; Tamini et al., 2015), while their discards quickly sink or are consumed (Kuepfer et al., 2022). Because albatrosses generally feed while on the water (González-Zevallos & Yorio, 2011), they must repeatedly take flight to catch up to the vessel where discards are more available. We speculate that when vessels are not continuously discarding (e.g. during shooting, hauling or batched discarding; Kuepfer et al., 2022), following patterns may be less regular and thus more easily missed by our models (see Supporting Information S6.4).

Our predictive models come with some important caveats. We suspect that some false positive vessel detections were actually true positive detections of hidden vessels (Supporting Information S6.3),

which occasionally occur in the southern Patagonian shelf (Arrizabalaga et al., 2019; Paolo et al., 2024; Welch et al., 2022). Moreover, our results only apply to black-browed albatrosses interacting with freezer trawlers presumed to be discarding waste. It is likely that vessel following behaviours appear different for other seabird species, fishery gear types and discarding strategies (Carneiro, Clark, et al., 2022; Collet et al., 2017; González-Zevallos & Yorio, 2011; Kuepfer et al., 2022). For example, the greatest risk of bycatch in longline fisheries comes not from discarding but from the setting of baited hooks (Anderson et al., 2011). Consequently, immersion patterns around longlines may be less regular than those around trawlers, especially for species that more frequently dive to capture prey (Frankish et al., 2021). Future studies should therefore

test whether similar immersion patterns can detect seabird-vessel interactions for other species and fisheries. Examination of regular patterns in diving and accelerometry data could also reveal other distinct behavioural signatures of vessel interaction.

4.3 | GLS-immersion logger error

GLS-immersion loggers produced imperfect immersion data that could nonetheless be used to predict vessel following. Many studies assume GLS-immersion data to be correct (Carneiro, Dias, et al., 2022; Ponchon et al., 2019; although see Darby et al., 2022), yet here we show a majority of GLS regularly overestimate the duration of wet periods (Supporting Information S2). This error generally occurred because devices stayed wet for too long after take-off, potentially because the feathers around the device retained enough seawater to confound the immersion detection. Although here we were able to correct this error using GPS tracks, future applications of our method should ideally not be limited to short-term datasets with high-resolution GPS. Fortunately, we found that even with uncorrected GLS data, our models were still able to detect vessel following based on our predefined objectives. In fact, the uncorrected GLS data unexpectedly improved the performance of Model 8 (corrected, bout-based), potentially because GLS error eliminated more false positives than true positives. Nevertheless, future studies should investigate how to detect and mitigate GLS-immersion error to reduce potential biases in seabird behaviour classification and vessel detection.

4.4 | Conservation implications

Our immersion-based approach to predicting vessel following has important implications for bycatch risk assessment. First, our findings suggest it is possible for seabird-fishery interaction analyses to rapidly incorporate larger and more demographically representative GLS datasets of seabird movement (Carneiro et al., 2020; Gianuca et al., 2017). GLS-immersion loggers are small, inexpensive, battery-efficient and unaffected by moult, meaning they can be deployed on non-breeding individuals for years (Ponchon et al., 2019; Weimerskirch et al., 2014), and on smaller species such as shearwaters (Guilford et al., 2012). Second, we demonstrate a modelling approach that works without tracking data from vessels, meaning it can overcome the lack of data from small-scale, artisanal, illegal, unreported and/or unregulated fisheries (IUU; Araújo et al., 2022; Paolo et al., 2024; Weimerskirch et al., 2020; Welch et al., 2022). Revealing seabird interactions with these fisheries is one of the principal challenges of seabird bycatch risk assessment today (Votier et al., 2023). Finally, we suggest that behavioural detection of fine-scale vessel interaction may provide a more realistic proxy for bycatch risk than proximity-based approaches (e.g. Carneiro, Clark, et al., 2022; Corbeau, Collet, Orgeret, et al., 2021). Our models ignore periods

during which seabirds may be near vessels but not at imminent risk of bycatch, instead focusing on the highest-risk periods of interaction that have previously only been studied using vessel-based observers (e.g. Kuepfer et al., 2022; Tamini et al., 2023).

By addressing multiple limitations inherent to seabird-fishery interaction analysis, our approach has the potential to improve bycatch risk assessments in many data-limited systems. However, further research is needed to determine whether immersion patterns could be diagnostic of vessel following in other species and fisheries.

AUTHOR CONTRIBUTIONS

Jonathan D. Rutter designed the methodology, analysed the data and led the writing of the manuscript. Jonathan D. Rutter, Ana P. B. Carneiro, Katrina J. Davis, Oliver Padget and Tim Guilford conceived the ideas. Paulo Catry, Louise Maurice and Tim Guilford collected the bird data. Katrina J. Davis and Tim Guilford supervised. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Albatross data are embargoed for 2 years in the Movebank Data Repository (<https://doi.org/10.5441/001/1.663>; GPS and immersion; Guilford et al., 2025a) and will be made publicly available on 3 July 2027. GPS data are currently available with permission via the BirdLife Seabird Tracking Database (<https://data.seabirdtracking.org/dataset/2410>; see also 2411 and 2412; Guilford et al., 2025b). Aggregated fisheries data, and up to 10 individual tracks per day, can be downloaded from Global Fishing Watch (<https://globalfishingwatch.org/map/>). More vessel tracks are available on request from Global Fishing Watch and BirdLife International. R scripts, static maps, animations and a subset of data are available via Zenodo (Rutter et al., 2025; <https://doi.org/10.5281/zenodo.15287690>) and GitHub (<https://github.com/jonathanrutter8/immersion-patterns>).

STATEMENT ON INCLUSION

Our study brings together authors from multiple countries. Although none are based in the Falklands, Paulo Catry works closely with the local government and fieldworkers on an annual basis. We have discussed this research on multiple occasions with Argentine colleagues who regularly engage with fisheries, and we have made sure to cite literature from Argentina and the Falklands.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information S1. R Scripts.

Supporting Information S2. Immersion correction.

Supporting Information S3. Immersion regularity metric.

Supporting Information S4. Random forest models.

Supporting Information S5. Bird-vessel interaction events.

Supporting Information S6. Dissecting model outputs.

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