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A probabilistic time geographic approach to quantifying seabird-vessel interactions

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Abstract

Accounting for uncertainty is essential for precautionary approaches to managing seabird bycatch in commercial fisheries. However, there is no existing mechanism to explicitly quantify the uncertainty of seabird-vessel interactions (i.e. co-occurrence in space and time). Here we develop a time geographic method to measure the probability of individual birds encountering (co-occurring within 30 km) and attending (within 5 km) individual fishing vessels. The approach involves creating voxel-based probabilistic space–time prisms (PSTPs) to model the movements of individual birds and vessels, with trajectory data from bird-borne GPS devices and vessel Automatic Identification Systems (AIS). We intersected these PSTPs to quantify the probability of interaction between bird-vessel pairs over time and space. We demonstrate the approach with a case study of interactions of Endangered Toroa (Antipodean Albatross; *Diomedea antipodensis antipodensis*) with pelagic longline vessels in part of the South Pacific high seas. We found 15 vessels within 150 km and 3 h of two birds, yet interaction occurred with only two of those vessels. We visualised the probability of encounter and attendance over time and space and determined that interactions lasted several hours each (up to 6.2–14.1 h attendance, 20.8–26.1 h encounter for one bird-vessel pair). Our time geographic approach adds to existing tools to quantify seabird bycatch risk by providing an explicit measure of uncertainty of seabird-vessel interactions. We provide a flexible methodological pathway and R scripts, the application of which would allow managers to estimate interaction probability for multiple marine species and fisheries, including those with lower-resolution positional datasets.

Introduction

Seabirds are one of the most threatened bird groups (Dias *et al.*, 2019). Nearly one-third of seabird species are listed as Vulnerable, Endangered or Critically Endangered, and half the species with a known trend are declining (IUCN, 2022). Incidental mortality in fisheries (hereafter, 'bycatch') is the highest-impact driver of population declines, affecting 100 species (Dias *et al.*, 2019). Bycatch occurs because seabirds spend much of their lives foraging at sea and are often attracted to the bait, catch and/or discards made available by fishing vessels (Clay *et al.*, 2019). In pelagic and demersal longline fisheries, seabirds can become caught on baited fishing hooks and drown (Brothers *et al.*, 2010); in trawl fisheries, they can fatally strike warp cables or become entangled while diving for food (Watkins, Petersen, & Ryan, 2008); and in gillnet fisheries, they can become entangled in nets (Žydelis, Small, & French, 2013). Longline fisheries are of particular conservation concern, with a conservative estimate of 160,000 to 300,000 seabird mortalities per year (Anderson *et al.*, 2011). Mitigation measures to reduce the risk of bycatch to seabirds have been developed, including night setting, weighted lines, hook-shielding devices and bird-scaring devices (ACAP Secretariat, 2021). Despite their proven efficacy, implementation and compliance with these measures have been insufficient, highlighting bycatch as a serious yet preventable threat (Juan-Jordá *et al.*, 2018; Clay *et al.*, 2019).

Ecological risk assessments (ERAs) are a critical tool for the development and implementation of best practice bycatch mitigation measures (Small, Waugh, & Phillips, 2013; Good *et al.*, 2020). ERAs characterise fisheries impacts on seabirds using data on observed bycatch events, seabird demographics and spatiotemporal overlap of seabirds and fisheries (Small, Waugh, & Phillips, 2013). These data can be uncertain for several reasons. Precise estimates of bycatch rates are difficult to acquire because bycatch events are statistically rare (Komoroske & Lewison, 2015) and fisheries observer coverage is spatiotemporally sparse worldwide (Anderson *et al*., 2011; Ewell *et al*., 2020). Furthermore, highly dispersed seabird populations are logistically difficult to monitor, and positional data for fishing vessels, derived from logbooks, Vessel Monitoring Systems (VMS) and Automatic Identification Systems (AIS), are not comprehensive (Le Bot, Lescroël, & Grémillet, 2018; GFW, 2022a). Such uncertainties, when not sufficiently accounted for, weaken the evidence base needed to implement precautionary bycatch management strategies. Thus, the most robust ERAs explicitly quantify uncertainty in their models (e.g. Richard, Abraham, & Berkenbusch, 2020), and studies continue to develop new methods to do so. For example, recent analyses have incorporated uncertainty into models of regional-level bycatch rates (Zhou & Liao, 2022), fleet- and vessel-level bycatch rates (Parsa *et al*., 2020), bycatch mitigation device efficacy (Gilman *et al*., 2022) and seabird population viability across a range of anthropogenic mortality scenarios (Miller *et al*., 2019).

Despite the range of methods that exist to quantify the uncertainty of bycatch risk, the uncertainty of interactions (here, defined as spatiotemporal co-occurrence) of seabirds and fishing vessels has been largely overlooked. This research gap is particularly concerning given the importance of seabird-fishery overlap analyses to seabird ERAs (Small, Waugh, & Phillips, 2013). The extent to which distributional overlap metrics correlate with bycatch risk is uncertain (Corbeau *et al*., 2021). Some studies, working with finer-scale data (generally <15 min sampling interval for birds), have quantified the duration of interactions between individual seabirds and individual vessels to provide a more realistic proxy for bycatch risk (e.g. Corbeau *et al*., 2021; Orben *et al*., 2021). Although these studies successfully reduce uncertainty of seabird-vessel interactions, they do not quantify uncertainty. Consequently, they are not scalable to lower-resolution tracking datasets, which are cheaper and more practical to obtain for seabirds that breed in remote locations and/or forage in areas beyond national jurisdiction (ABNJ). Indeed, most studies of seabird-vessel interaction examine breeding birds that return to their nests within days or weeks, overlooking non-breeding cohorts of highly migratory species that may be at disproportionately high risk of bycatch (Gianuca *et al*., 2017; Carneiro *et al*., 2020). The development of methods to account for the uncertainty of seabird-vessel interactions is an important next step for ERAs, especially for those relying on lower-resolution seabird tracks.

The rapidly developing field of time geography offers an analytical methodology with potential for improving bycatch risk estimates by incorporating a measure of uncertainty. Time geographic methods model movement within spatiotemporal constraints (Miller, 2018); in particular, probabilistic space–time prisms (PSTPs) model individual trajectories not as sequences of points, but as probability distributions in three-dimensional space–time (Fig. 1a; Winter & Yin, 2010). A PSTP consists of an infinite number of two-dimensional space–time disks, each of which captures the probability that a moving agent was in a specific location at a specific time, based on the agent's maximum velocity and a distance weighting function that reflects its movement qualities (Fig. 1b; Downs *et al*., 2014a). To ease computation, PSTPs can be discretised into 'voxels', which are analogous to pixels but with an additional vertical time dimension (Downs *et al*., 2014a). Multiple voxel-based PSTPs can be intersected to calculate the probability that two or more moving agents interacted at a specific time and location (Downs *et al*., 2014b) or within a certain distance (Yin *et al*., 2018). Probabilistic time geographic approaches have proven useful for many applications including behavioural ecology (Loraamm, 2020), vehicle traffic modelling (Chen *et al*., 2013) and COVID-19 exposure risk (Li *et al*., 2021). To our knowledge, they have not been used to measure the interaction probability of more than one type of moving agent.

Here we apply time geography to model the interactions of individual seabirds and fishing vessels with explicit measures of interaction uncertainty. We introduce a flexible methodological pathway consisting of efficient procedures for querying fishing vessel trajectory data, creating voxel-based PSTPs and quantifying seabird-vessel interactions probabilistically. Our methodology is designed to be scalable to a range of species and fisheries. We demonstrate proof of concept through a case study of an Endangered albatross species, and we provide R scripts to enable further implementation of the approach.

Materials and methods

Methodological approach

Our methodological approach detects small-scale bird-vessel interactions from movement data across large spatiotemporal scales (Supporting Information 1). We first used trajectory data for birds to query trajectory data for nearby vessels. Then, we created and intersected PSTPs with coarse-resolution voxels for each bird-vessel pair to identify which pairs interacted. For each pair with a nonzero probability of interaction, we created finer-resolution PSTPs from which we could detect interactions more accurately, but at a higher computational cost. The outputs from these analyses included time series and maps of interaction probability, as well as duration of interaction.

We applied this approach to a case study of interactions between Toroa (Antipodean Albatross; *Diomedea antipodensis antipodensis*) and pelagic longline vessels. Toroa breed on Moutere Mahue (Antipodes Islands) of Aotearoa (New Zealand), and their range stretches from the South Australian Bight to the west coast of South America (Walker, Elliott, & Nicholls, 2006). Its population is declining at 5% per annum (Richard, 2021), primarily because of bycatch of females in pelagic longline fisheries (Bose & Debski, 2021). The species is listed as of priority concern under the Agreement on the Conservation of Albatrosses and Petrels (ACAP); on Appendix I of the Convention on Migratory Species (CMS; ACAP PaCSWG6, 2021); Nationally Critical in Aotearoa (Robertson *et al.*, 2017) and Endangered by the IUCN (2022; together with *D. a. gibsoni*).

All analyses were carried out with custom scripts in R V4.2.0 (R Core Team, 2022; Supporting Information 2; github.com/jonathanrutter8/BVTimeGeography).

Study area and period

We defined a study area and period to test our methodological approach because we were limited in the total number of days for which we could acquire vessel data. Our study area included all ABNJ west and east of the Aotearoa EEZ (between 150°E and 165°W longitude, and 25°S and 45°S latitude; see Fig. 3a in Section 3), previously identified as high risk for Antipodean albatross bycatch based on an analysis of daily overlap with pelagic longline fishing effort (Bose & Debski, 2021). Our study period, May to August 2019, was chosen to coincide with the season when most interactions between Toroa and fishing vessels occur (Bose & Debski, 2021).

Bird location data

Toroa location data was collected throughout 2019 using 10 tags deployed at their Moutere Mahue breeding colony between January and February. Incubating female Toroa were tagged with solar-powered Rainier S20 tags equipped with both GPS and Argos (PTT) location systems (Elliott & Walker, 2019). The tags weighed 20 g, well below the 3% body mass threshold suggested for tagging flying seabirds (Phillips, Xavier, & Croxall, 2003). Tags were attached using a bespoke PVC base plate secured to the back feathers using Tesa tape. Tags were programmed to record one GPS fix every 40 minutes during the day, and one every 2 h overnight. All fieldwork was approved by Kaitiaki Rōpū ki Murihiku and the New Zealand Department of Conservation, including its institutional Animal Ethics Committee (Gummer, 2013). Further details of data collection are available in Elliott & Walker (2019, 2020).

We checked and filtered bird location data following the protocol established by Bose & Debski (2021). We applied a speed filter of 50 m/s (180 km/h) and discarded low-quality Argos-derived locations (LC A, B, Z; LC 0 within 12 h of high-quality locations). We clipped tracks to the study area and period and then removed isolated fixes (over 150 km and 3 h away from adjacent fixes) between which there would be excessive positional uncertainty. Next, using publicly available daily fishing effort data from Global Fishing Watch (GFW) at 0.01° spatial resolution (GFW, 2022b), we conducted a preliminary point-based overlap analysis to determine which days of our study period had high overlap between bird tracks and fishing effort, suggesting potential for bird-vessel interaction (for full methodology, see Bose & Debski, 2021). We narrowed our analysis to 5 days with particularly high overlap (8–12 July 2019). Two individual Toroa – one breeding female (Blue-61b) and one non-breeding female (Blue-07b) – occurred in our study area during this period.

Vessel location data

GFW provided AIS-derived positions of reporting pelagic longline vessels within 150 km and 3 h of each bird

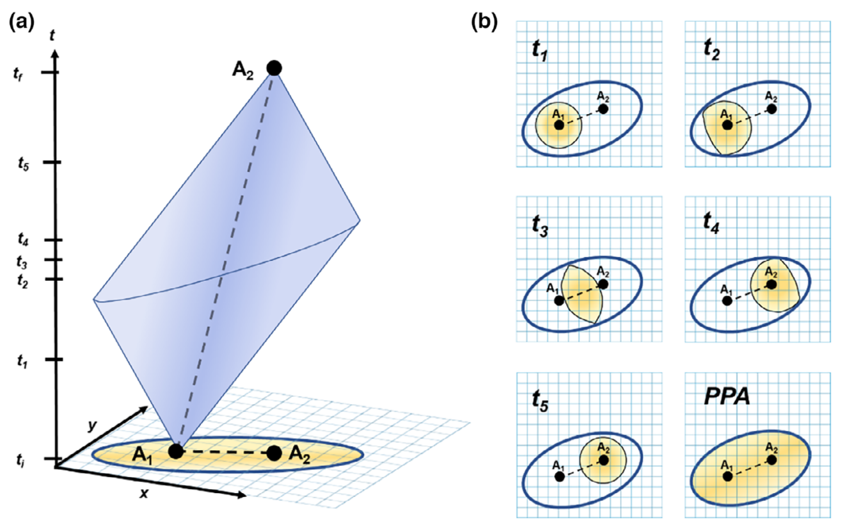

Figure 1 (a) Probabilistic space–time prism (PSTP) representing all accessible areas of moving agent A between positions A_1 and A_2 at times t_i and t_f respectively, shown here in an *x-y-t* space–time cube. The boundaries of the prism represent the extent of the moving agent's accessible area in space and time. The shading depicts its probability of occurrence, which is higher towards the linearly interpolated space–time path between A_1 and A_2 (denoted by the dotted line). (b) Space–time disks for five time steps along the PSTP. The yellow ellipse represents the union of all space–time disks in space, also known as the potential path area (PPA) between A_1 and A_2.

position, which we obtained by linearly interpolating our bird tracks to one position every 10 minutes. We chose these conservative spatial and temporal buffers to balance the uncertainty of bird positions between distant GPS fixes with the need to keep our data query to a manageable size. We divided vessel positions into 'sub-trajectories' determined by unique bird ID, unique vessel identifier (MMSI), and a maximum time interval of 4 h between adjacent positions.

Creating voxel-based probabilistic space–time prisms

Model parameters

We defined three parameters prior to creation of voxel-based PSTPs: voxel size, maximum velocity, and distance weighting function. First, we selected three voxel sizes based on type of interaction analysis (see Section 2.6.1): 30 km × 30 km × 30 min (30 × 30 × 30), 5 km × 5 km × 5 min (5 × 5 × 5) and 1 km × 1 km × 1 min (1 × 1 × 1). We retained the 1 km^2:1 min ratio for all voxel sizes because this corresponded to a velocity of 60 km/h, which was well above the observed average velocities at all vessel and most bird positions in the dataset.

Second, we set maximum velocities for birds and vessels. For birds, we set a constant maximum velocity of 30 m/s (108 km/h) because this roughly corresponds to the maximum flight speed of Wandering Albatrosses (*Diomedea exulans*; Merkel *et al.*, 2016). Vessels tend to move less stochastically between positions than birds, and their positions were generally at a higher temporal resolution in the dataset. They also may exhibit individual variations in maximum velocity. Thus, rather than setting a constant maximum velocity, we set a velocity multiplier of 1.5, which we multiplied by the average velocity calculated between AIS positions to produce a maximum velocity value that varied along each vessel trajectory (see Downs *et al.*, 2014b; Yin *et al.*, 2018).

Third, we selected different distance weighting functions for birds and vessels to produce probability distributions for their locations at each time step between known positions (Supporting Information 3). For vessels, we assumed the probability of occurrence varied inversely with distance from the linearly interpolated trajectory path (Yu *et al.*, 2019). For birds, we employed dynamic Brownian Bridge movement models (dBBMMs) whereby the Gaussian distance weighting function varied according to animal behaviour, GPS device error, and time between GPS fixes (Kranstauber *et al.*, 2012).

Computational approach

To create voxel-based PSTPs, we drew upon methods for visualising stacked space–time densities (Demšar *et al.*, 2015) and the ArcGIS Pro PySTPrism toolbox (Loraamm *et al.*, 2020). Our approach consisted of three steps (Supporting Information 4): First, we identified unique bird-vessel pairs, with each vessel sub-trajectory associated with a single bird trajectory with similar start and end times. Second, using the R package 'move' (Kranstauber *et al.*, 2022), we created regular trajectories (i.e. with constant time steps that corresponded to voxel size) for paired birds and vessels. Third, we created one bird and one vessel voxel-based PSTP for each trajectory pair based on the parameters outlined in Section 2.5.1. PSTP creation involved the following: for each interpolated position between known positions (GPS fixes), we calculated the accessible area of the bird or vessel (determined by maximum velocity) and its probability distribution within that area (determined by distance weighting function). PSTPs were stored as raster stacks consisting of one raster layer per time step, each representing a space–time disk.

Interaction analyses

Voxel overlap-based interaction

We analysed bird-vessel interaction with two different methods (Fig. 2). First, following Downs *et al.* (2014b), we implemented voxel overlap-based (VOB) interaction analysis, which defines interaction as the co-occurrence of a bird and a vessel within a single voxel (Supporting Information 5). For albatrosses, interaction with vessels has previously been subset into 'encounter' (co-occurrence within 30 km, corresponding to the limit of albatrosses' visual detection range in daytime, when they are most active) and 'attendance' (within 3–5 km, the range of albatross foraging behaviour near vessels; Fig. 2a; Corbeau *et al.*, 2021, Collet, Patrick, & Weimerskirch, 2017). Vessel 'attendance' is synonymous with vessel 'association' (Orben *et al.*, 2021) and 'visit' (Carneiro *et al.*, 2022). We set two different voxel sizes accordingly: 30 × 30 × 30 voxels corresponded to the spatial scale of encounter events, while 5 × 5 × 5 voxels corresponded to the scale of attendances (Fig. 2b). For each voxel, we calculated the probability of interaction by multiplying the probability of bird occurrence by the probability of vessel occurrence obtained from their respective PSTPs. Thus, depending on voxel size, voxel overlap suggests an encounter or attendance at a specific time and location.

Distance threshold-based interaction

We also implemented a more accurate model of interaction using high resolution (1 × 1 × 1) voxels to measure bird-vessel interaction within distance thresholds of both 30 km (for encounters) and 5 km (for attendances; Fig. 2b; Supporting Information 5). This distance threshold-based (DTB) interaction analysis differs from VOB analysis because it accounts for the probability of interaction of moving agents that occur in different voxels (Yin *et al.*, 2018). Thus, voxels can be smaller than those used for VOB analysis. With interaction probabilities no longer linked to voxel size, DTB analysis yields more realistic representations of encounter and attendance events. However, this method requires significantly more computation time. We therefore limited DTB analyses to the bird-vessel pairs identified by VOB analysis as having interacted. For each pair, we found the first and

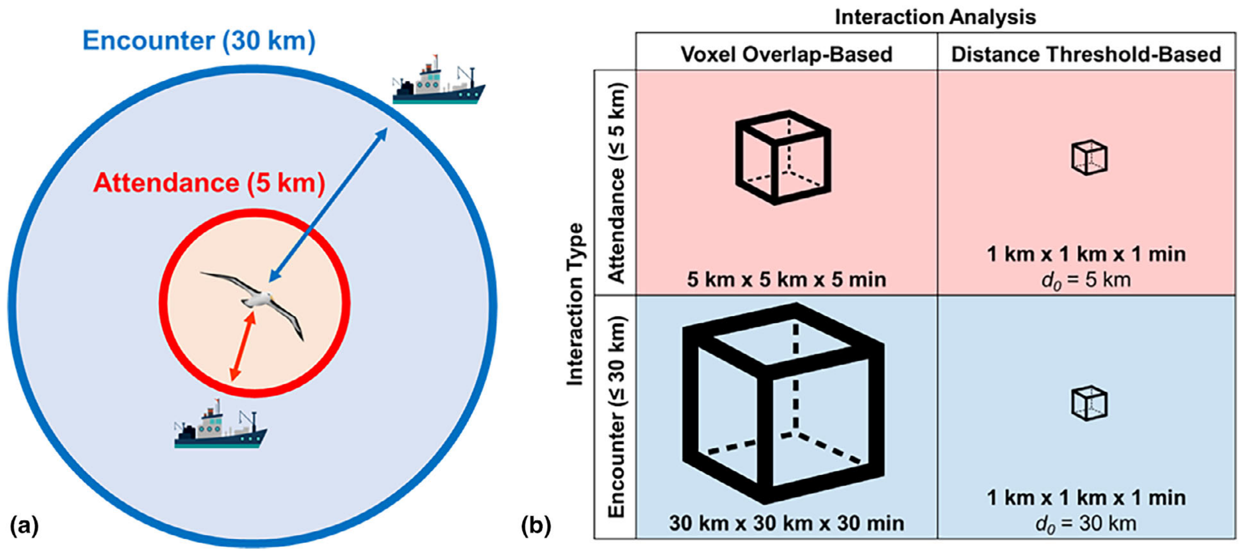

Figure 2 (a) The two types of seabird-vessel interaction examined in this case study, encounter and attendance. (b) Four approaches to constructing voxel-based PSTPs, depending on interaction type (encounter/attendance) and analysis (VOB/DTB).

last timestamps of nonzero VOB encounter probability, buffered each timestamp by 90 minutes, and re-subset the bird and vessel trajectories. Then, we repeated the procedure to create PSTPs with 1 × 1 × 1 voxels (Section 2.5.2).

We aggregated the outputs from both VOB and DTB analyses to quantify (1) probability of interaction over time (i.e., time series), (2) probability of interaction over space (i.e., maps) and (3) duration of interaction, based on probability thresholds of 2.5%, 50% and 97.5% (Supporting Information 6; Buchin *et al*., 2012, Downs *et al*., 2014b). For comparison, we also calculated duration of interaction through a non-time geographic approach (i.e., without accounting for uncertainty) as follows: First, we linearly interpolated all bird and vessel tracks to 1-minute intervals; second, we calculated the Euclidean distance between simultaneous bird and vessel points; and third, we found the number of minutes that each bird and vessel point co-occurred within 30 km and 5 km of each other.

Results

Bird and vessel trajectories

Our GFW data query returned trajectories of 15 pelagic longline vessels from four flag states (Fig. 3). Vessel trajectories consisted of AIS-derived positions with highly variable time intervals (mean 6.2 ± 39.5 min); bird trajectories tended to have coarser temporal resolution (daytime sampling interval ~ 40 min, overall mean 65.4 ± 112.0 min). Toroa Blue-07b was near four vessels in Te Tai-o-Rēhua (Tasman Sea; Fig. 3b), and Toroa Blue-61b was near 11 vessels east of Rangitāhua (Kermadec Islands; Fig. 3c). Both bird trajectories intersected in space with multiple vessel trajectories, without accounting for time. Time series of each bird's motion variance are included in Supporting Information 7.

Creation of voxel-based PSTPs

We created 92 voxel-based PSTPs to model trajectories of birds and vessels. Subsetting of vessel trajectories returned 20 sub-trajectories, meaning some of the 15 vessels had >4-hour gaps between two positions. We created two PSTPs (5 × 5 × 5 and 30 × 30 × 30) for each vessel sub-trajectory and its corresponding bird sub-trajectory (total 88). After VOB interaction analysis revealed two bird-vessel pairs with interaction, we created PSTPs with 1 × 1 × 1 voxels for portions of those four bird and vessel sub-trajectories. We did not create 1 × 1 × 1 PSTPs for any other bird-vessel pairs to reduce unnecessary computational demand. Supporting Information 8 contains details on the centre point location, temporal extent, size and computation time of the space–time cubes containing each bird-vessel PSTP pair. Supporting Information 9 illustrates a portion of one of Blue-61b's PSTPs, depicted as a series of space–time disks at discrete moments in time.

Quantification of bird-vessel interaction

VOB interaction analysis showed that Blue-61b interacted for several hours with two of the 11 pelagic longline vessels (Vessel 7, sub-trajectory 9; Vessel 10, sub-trajectory 14), whereas Blue-07b had zero probability of interaction with all four nearby vessels. We analysed DTB interactions for the portions of sub-trajectories 9 and 14 during which there was probability of interaction detected by VOB analysis (Supporting Information 10).

Probability of interaction over time

Blue-61b spent several hours on the evening of 9 July local time attending Vessel 7 while encountering Vessel 10, which on closer inspection turned out to be travelling in parallel

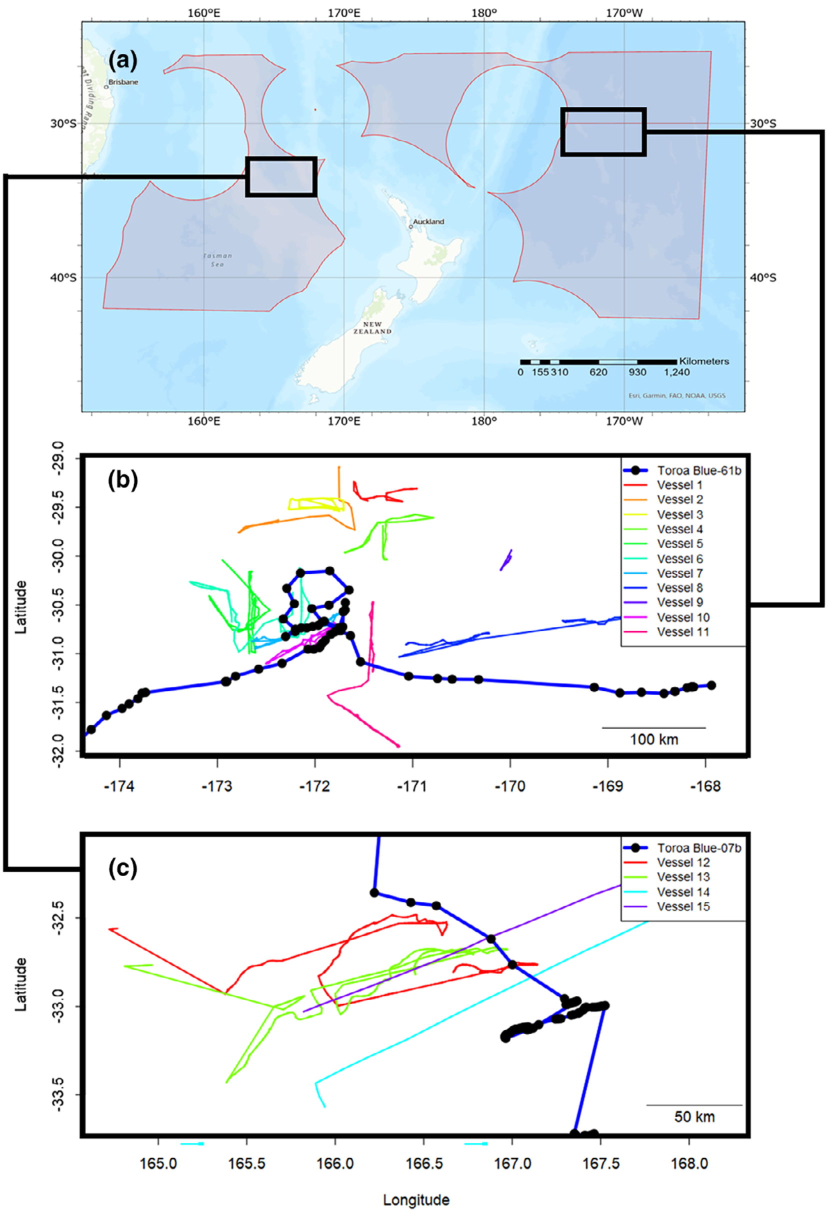

Figure 3 (a) Study area, with subsets showing the GPS fixes (black points) and linearly interpolated paths (blue lines) of two Toroa, (b) Blue-61b and (c) Blue-07b, from 8 to 12 July 2019. Queried AIS-derived vessel trajectories from this period are also shown.

with Vessel 7 roughly 14 km away. She then switched to attending Vessel 10, which was already within visual range, for several hours on the morning of 10 July. As expected, attendance probabilities during daylight hours were highest around the times of GPS fixes. Encounter probabilities remained at 100% for stretches of several hours when, given our parameters, it was impossible for her to fly >30 km from the vessel. In between the two attendance periods, Blue-61b's location was uncertain due to a lack of GPS fixes overnight. Nevertheless, there was a high probability of encounter and nonzero probability of attendance during this period (Fig. 4).

DTB analysis (Fig. 4d–f) provided more robust estimations of interaction probability than VOB (Fig. 4a–c). DTB time series were smoother and more consistent than VOB time series, and they occasionally detected interaction where VOB analyses did not (e.g. encounter with Vessel 10 before 10 July 00:00). However, DTB analyses took days to compute, whereas VOB analyses took minutes (Supporting Information 10).

Probability of interaction over space

Maps of VOB attendance and encounter probabilities illustrated where in the seascape interaction likely occurred, although DTB maps provided far more detail (Fig. 5). When Blue-61b was near a vessel and recording frequent GPS fixes, DTB maps highlighted the vessel trajectory with a high precision. Comparing the DTB maps of interaction (Fig. 5) to their time series (Fig. 4) shows that Blue-61b spent hours travelling northeast with Vessel 7, while still encountering Vessel 10 which was travelling in parallel nearby. After an overnight period with uncertain location, the bird then travelled back towards the southwest while attending Vessel 10.

Duration of interaction

Blue-61b interacted with both Vessel 7 and Vessel 10 for several hours during the study period (Fig. 6; Supporting Information 10). Estimated duration of attendance and encounter was higher with Vessel 10. For all attendance and encounter duration measures, VOB analysis returned lower estimates than DTB. For Vessel 10 in particular, DTB analysis estimated 24.0 encounter hours and 9.1 attendance hours at a 50% probability threshold, compared to 13.0 encounter hours and 5.4 attendance hours estimated by VOB analysis. These durations represented 20.0%, 7.6%, 10.8% and 4.5% of the study period respectively. Further exploration revealed that VOB duration estimates were not consistently closer to DTB estimates when PSTPs were created with 1-minute time steps (i.e. 5 × 5 × 1 and 30 × 30 × 1 voxels). As expected, uncertainty of these metrics, illustrated in Fig. 6 as error bars from 97.5 to 2.5% probability thresholds, was higher for attendance than encounter across all methods and vessels. Time series of interaction duration estimates, calculated within smaller temporal windows, are included in Supporting Information 11.

Non-time geographic analysis, based on distance between linearly interpolated bird and vessel positions, produced similar estimates of interaction duration to DTB analysis at the 50% probability threshold (Fig. 6). However, these methods did not provide the probability of these estimates, nor a range of possible durations.

Discussion

This study presents a novel application of probabilistic time geographic methods to quantify interactions between seabirds and fishing vessels. Probabilistic approaches allow for the measurement of uncertainty in seabird and vessel positions between location fixes. Previous studies have reduced uncertainty by increasing data resolution, with some GPS devices recording positions once every 2 min (e.g. Weimerskirch *et al.*, 2020). However, high-resolution datasets are rarely available. We address this issue by employing voxel-based PSTPs, which model seabird and vessel trajectories based on predefined movement parameters. We apply this approach to a case study of Toroa interactions with pelagic longline fisheries. Our methodological pathway and associated R scripts (Supporting Information 1 and 2; github.com/jonathanrutter8/BVTimeGeography) are adaptable to other species and fisheries.

Voxel-based PSTPs have not previously been applied to examine animal-vessel interactions. Previous studies have used PSTPs to measure animal interactions with static roadways (Loraamm & Downs, 2016; Loraamm, Downs, & Lamb, 2018) and collision risk between vessels (Yu *et al.*, 2019). Other studies have quantified albatross-vessel interactions using methods resembling time geography, but without measurement of probability. Torres *et al.* (2011) measured the overlap of albatross positions with the accessible areas of vessels between VMS fixes; this is equivalent to constructing a non-probabilistic space–time prism for vessels alone. Sztukowski *et al.* (2017) overlapped the 95% utilisation distributions of albatrosses and vessels at different time steps based on bivariate Gaussian bridges; although they did not use PSTPs, this was effectively a voxel-based overlap analysis. Our method improves upon these analyses by creating PSTPs for both seabirds and vessels. To our knowledge, this is the first application of PSTPs to model interactions between two different types of moving agent. It is also the first application of dBBMMs (Kranstauber *et al.*, 2012) within a time geographic framework, building upon Song & Miller (2014). These advances lay the groundwork for future studies of not only fisheries bycatch, but other diverse forms of interaction between two uncertain moving agents, from vehicle strikes to whale watching.

Our results provide key insights into the bycatch risk faced by two individual Toroa. Through time series and maps of interaction probabilities (Figs 4 and 5), our analysis clearly showed how risk varied over space and time. At night, when several hours passed without a GPS fix, there was greater uncertainty of interaction. Nevertheless, our analysis provided meaningful estimates of nonzero interaction probability during this time, showing its utility for low-resolution data. We also quantified the magnitude of bycatch risk exposure through estimates of encounter and attendance duration at multiple probability thresholds (Fig. 6). These estimates improved upon those of non-time geographic linear interpolation methods, which may provide plausible measures of duration but cannot quantify the uncertainty of those measures. DTB interaction analysis produced higher duration estimates than VOB analysis, likely because VOB estimates are dependent on the resolution and spatial layout of the voxel grid. For example, if a bird was located 3 km away from a vessel but happened to fall in an adjacent 30 × 30 × 30 voxel, VOB analysis would not detect an encounter.

Computation time was a key consideration in our use of both VOB and DTB analysis. Despite consistently underestimating interaction duration, VOB analysis was an efficient method for identifying approximate interaction times and locations. DTB analysis was inherently more accurate, but increased computation time and memory requirements by multiple orders of magnitude over VOB (Supporting Information 8 and 10). In this study, DTB analysis took multiple days. However, computation time was inflated for two reasons: First, unexpectedly, no GPS fixes were transmitted overnight for this specific bird and time period, resulting in an unusually large PSTP to fill the gap. We chose to keep

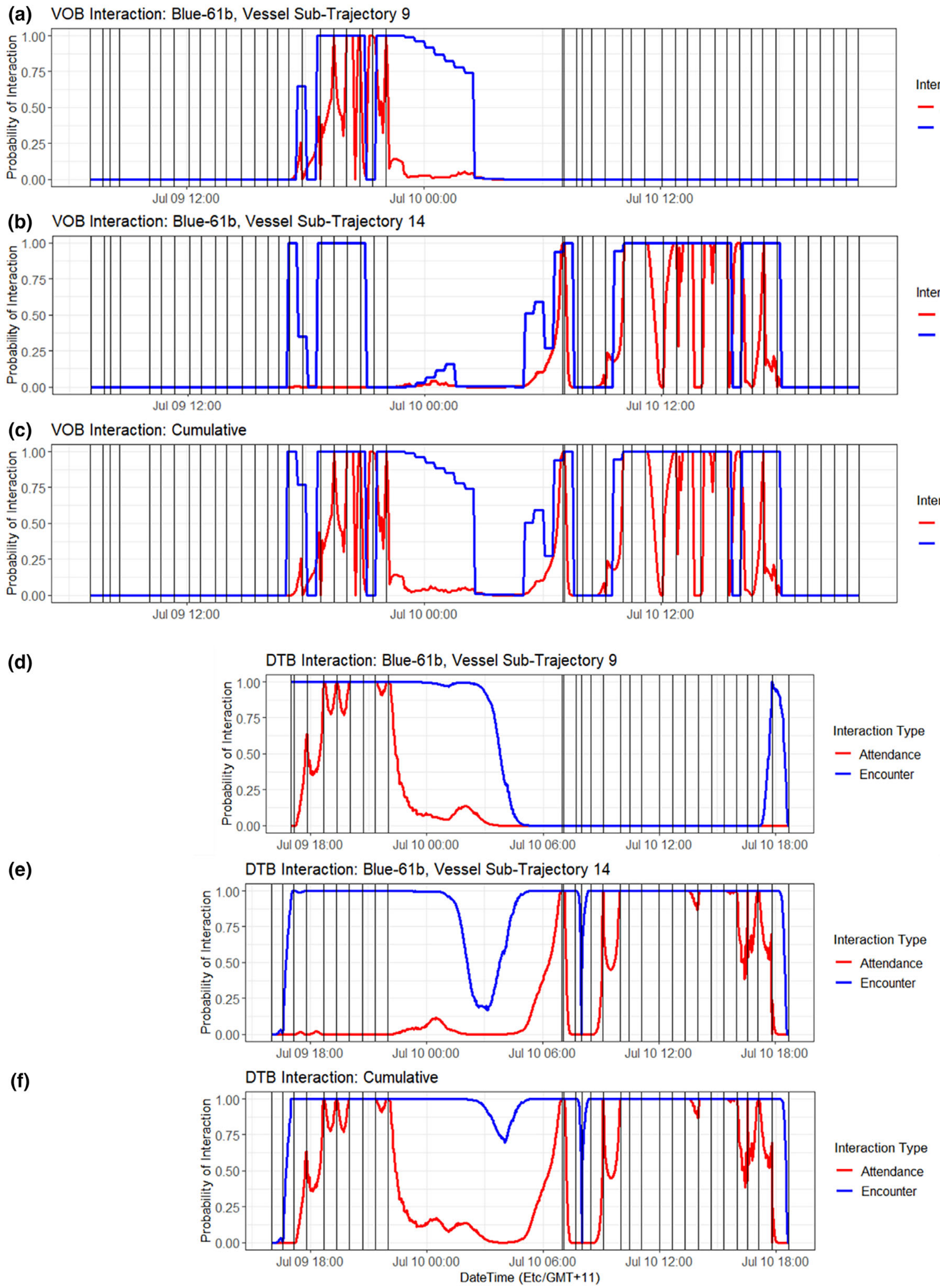
(a)
VOB Interaction: Blue-61b, Vessel Sub-Trajectory 9
(b)
VOB Interaction: Blue-61b, Vessel Sub-Trajectory 14
(c)
VOB Interaction: Cumulative
(d)
DTB Interaction: Blue-61b, Vessel Sub-Trajectory 9
(e)
DTB Interaction: Blue-61b, Vessel Sub-Trajectory 14
(f)
DTB Interaction: Cumulative
Probability of Interaction
0.00
0.25
0.50
0.75
1.00
Jul 09 12:00
Jul 10 00:00
Jul 10 12:00
Jul 09 18:00
Jul 10 06:00
Jul 10 18:00
DateTime (Etc/GMT+11)
Interaction Type
Attendance
Encounter

Figure 4 Time series of interaction probabilities between Blue-61b and (a and d) sub-trajectory 9 (Vessel 7), (b and e) sub-trajectory 14 (Vessel 10) and (c and f) both vessels cumulatively, calculated through VOB analysis (a–c) and DTB analysis (d–f). Vertical black lines denote times of albatross GPS fixes. Note that for VOB analysis, Encounter probabilities were computed over larger temporal steps than Attendance probabilities (30 min vs 5 min). DTB analyses were limited to time steps with expected interaction and were thus computed over smaller temporal extents than VOB analyses.

this overnight period for demonstration purposes, but we could have easily reduced computation time by splitting the bird's trajectory as we did with vessels (Section 2.4). Second, our algorithms compute each interaction in parallel. We had only two interactions to compute, but we could have added many more with little effect on computation time (subject to number of cores available). Nevertheless, we still suggest using VOB analysis to focus subsequent DTB analyses on seabird-vessel pairs with confirmed interaction, as we have done here.

Although widespread application of time geography to ERAs is possible in theory, future applications of our approach require consideration of fisheries data availability. If cost or memory are limiting factors, we suggest narrowing time geographic analysis only to times and areas of high interest for management. For our case study, we identified these areas by first analysing seabird-fishery overlap with publicly available gridded GFW fishing effort data (see Bose & Debski, 2021). Future studies could further reduce data requirements by reducing the spatiotemporal buffer around seabird tracks, given that most pelagic longline vessels within a 150 km and 3 h buffer did not interact with the tagged Toroa. Furthermore, even when raw AIS trajectories are available, their coverage is not comprehensive. For example, smaller vessels generally do not use AIS (GFW, 2022a), and many illegal, unreported or unregulated vessels have turned the system off (Weimerskirch *et al*., 2020). These fisheries represent a significant gap in understanding of seabird bycatch worldwide (Pott & Wiedenfeld, 2017), but future time geographic studies of these fisheries would require positional data of vessels from sources beyond AIS.

Applications of the methodology presented here would also benefit from further consideration of input parameters. Here we defined two types of bird-vessel interaction based on fixed distance thresholds. These thresholds could vary by species and even by time; at night, for example, a vessel 'encounter' may occur at distances less than 30 km (Collet, Patrick, & Weimerskirch, 2017). We also defined a constant maximum velocity for Toroa and used a Gaussian distance weighting function (i.e. a dBBMM; Kranstauber *et al*., 2012) to calculate occurrence probability in each voxel. For vessels, we set a velocity multiplier and used an inverse distance weighting function. For both Toroa and vessels, we linearly interpolated movement paths between known positions. Validation of these parameters, including computation and propagation of their uncertainty, is important for larger-scale applications of our approach, especially those using lower-resolution data. Validation methods may include model comparison (Fleming *et al*., 2016) and down-sampling high-resolution GPS data. Future studies could incorporate non-linear interpolation of movement paths (Long, 2016) and variable maximum velocity of seabirds based on behavioural state. Additional movement parameters, such as environmental covariates within movement models (see Long, 2018; Kranstauber, 2019) and kinematic constraints to vessel movement (Kuijpers, Miller, & Othman, 2017), could also be used. For all such parameters, increases in model accuracy must be weighed against corresponding increases in computational demands and model complexity.

Management implications

Seabird bycatch is an ongoing conservation challenge that demands innovative solutions. Observer coverage of fisheries is extremely limited (Anderson *et al*., 2011; Ewell *et al*., 2020), and bycatch mitigation implementation is poor in many fisheries (BirdLife International, 2021). Applied within national and international ERAs, our approach could contribute to prioritising bycatch mitigation efforts. For example, identifying high-risk seasons, areas, seabirds, and vessels by their probability and duration of bird-vessel interaction can help develop area-based management tools such as marine protected areas (Oppel *et al*., 2018) and facilitate outreach efforts to specific fisheries to increase compliance with best practice mitigation measures. Programmes to assess fisheries against Marine Stewardship Council standards (https://www.msc.org/) and guide subsequent corrective actions may also benefit from this information.

Operationalising the methods presented here can inform conservation negotiations at the international level. Multilateral instruments such as ACAP have successfully reduced bycatch by advocating for the uptake of best practice mitigation measures (ACAP Secretariat, 2021). However, many regional fisheries management organisations (RFMOs) in which large fishing nations participate fall short of requiring best practice measures (Juan-Jordá *et al*., 2018), leaving some nations to seek alternative governance tools. Aotearoa, for example, has recently adopted a Memorandum of Understanding on seabird conservation with Spain aimed at reducing albatross bycatch (NZDOC, 2021), but many of the vessels posing risk to Toroa are flagged to other countries (Bose & Debski, 2021). Negotiations for future agreements are more likely to succeed with clear evidence of bycatch risk in specific fisheries. Our time geographic approach can provide compelling evidence of high-risk seabird-vessel interactions in ABNJ even when available data are sparse. In this way, our approach could empower management of a threat that is inherently uncertain, to ensure a less uncertain future for seabirds.

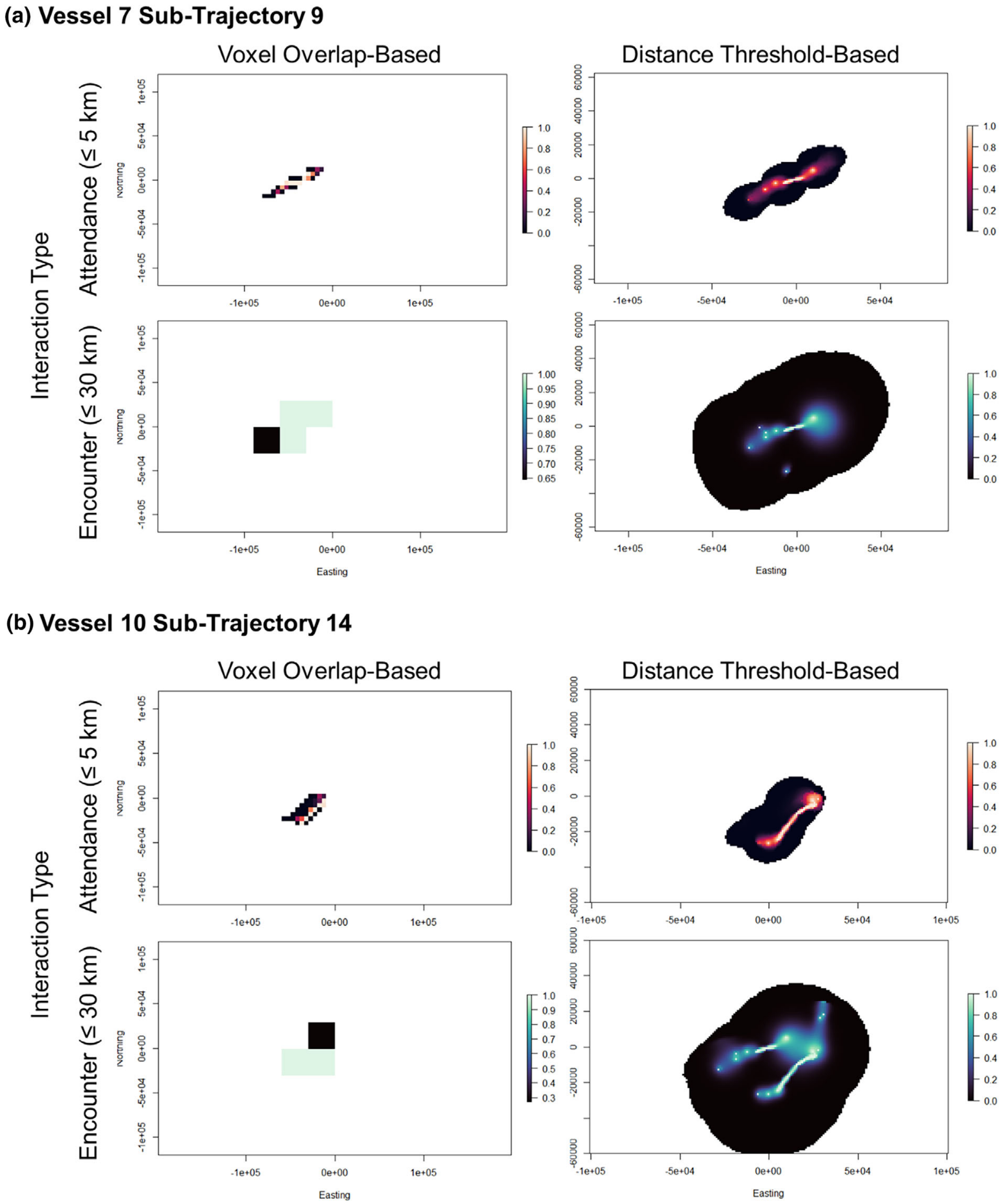

Figure 5 Maps of attendance and encounter probabilities between Blue-61b and (a) sub-trajectory 9 (Vessel 7) and (b) sub-trajectory 14 (Vessel 10). Left: VOB analyses. Right: DTB analyses. Coordinates are measured in metres from the centre point of the space–time cube shown.

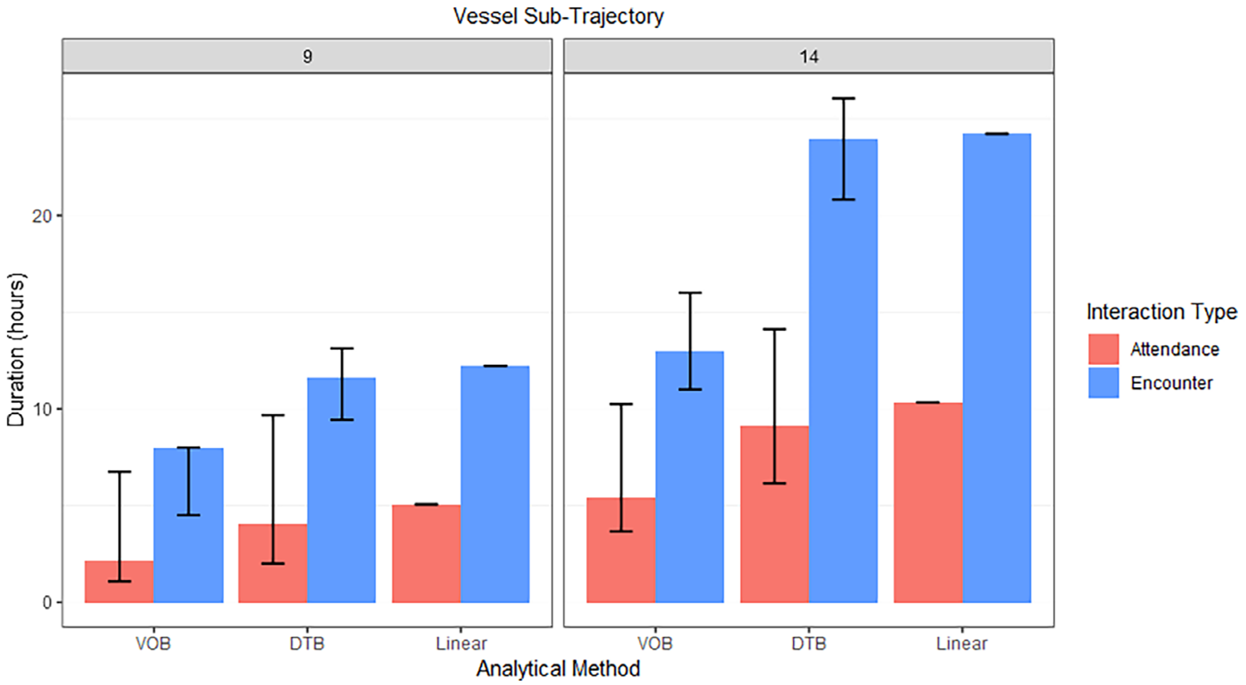

Figure 6 Blue-61b's duration of attendance and encounter with sub-trajectories 9 and 14 (representing Vessels 7 and 10, respectively), estimated through VOB, DTB and non-time geographic linear interpolation (Linear) methods. For VOB and DTB, coloured bars represent interaction at a 50% probability threshold; error bars represent the interval from 97.5 to 2.5% probability. Linear analysis provided no measure of uncertainty, hence the lack of error bars.

Statement on inclusion

Our study brings together an international group of authors, including scientists based in the country where data collection occurred. The authors represent a diverse set of academic, governmental and non-governmental perspectives; several are engaged in international institutions through which results of our study will be applied. All Toroa research, including this work, is disseminated to and discussed with Kāi Tahu, the iwi (Māori tribe) holding kaitiakitanga (guardianship) and rangatiratanga (sovereignty) over Toroa and Moutere Mahue, prior to publication through regular Toroa hui (meetings).

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Authors' contributions

J.D.R., S.B.B., S.B., A.P.B.C., B.L.C., I.D., J.H.F. and S.J.P. conceived the ideas; J.D.R. designed methodology, analysed the data and led the writing of the manuscript; A.P.B.C. and B.L.C. provided fisheries data; G.E. and K.W. collected bird data; S.J.P supervised. All authors contributed critically to the drafts and gave final approval for publication.

Data availability statement

Full seabird tracks are available through an interactive Shiny App (https://docnewzealand.shinyapps.io/antipodeanalbatross/; NZDOC and FNZ, 2022). Publicly available fishing effort data can be downloaded from Global Fishing Watch (https://globalfishingwatch.org/map; GFW, 2022b). R Scripts are available on GitHub (https://github.com/jonathanrutter8/BVTimeGeography). Vessel tracking data is available on request from Global Fishing Watch and BirdLife International.

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Supporting information

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

Supporting Information 1. Methodological approach.
Supporting Information 2. R scripts.
Supporting Information 3. Distance weighting functions.
Supporting Information 4. Computational approach to creating voxel-based PSTPs.
Supporting Information 5. Interaction analyses.
Supporting Information 6. Analytical outputs.
Supporting Information 7. Time series of motion variance.
Supporting Information 8. Table of space-time cubes.
Supporting Information 9. Selected space-time disks.
Supporting Information 10. Table of interactions.
Supporting Information 11. Interaction duration time series.