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Regional connectivity and spatial densities of drifting fish aggregating devices, simulated from fishing events in the Western and Central Pacific Ocean

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Abstract

The increased use of drifting Fish Aggregating Devices (dFADs) by tuna purse seine fleets in recent years has supported considerable catches of these species. A greater understanding of the spatiotemporal dynamics of these objects as they drift with ocean currents is critical for understanding historical changes in fishing power, spatial management, and examining the effect of ambient dFAD density on catch and effort. Here, dFAD dynamics were estimated for all floating object sets made by purse seiners in the Western and Central Pacific Ocean during 2016 and 2017. The drift trajectories of these floating objects prior to the observed fishing events were estimated by seeding virtual Lagrangian particles within a state-of-the-art hydrodynamics model, and simulating their movements backwards in time. Resulting trajectory distributions are similar to observed dFAD trajectories from the same period. The approach provides spatial density estimates in areas where observed dFAD data are incomplete, particularly in the exclusive economic zone (EEZ) of Howland and Baker Islands, and certain high seas areas. We provide estimates of inter-EEZ connectivity of dFADs, which highlight the fact that dFADs set upon in small EEZs such as Nauru and Howland and Baker Islands are likely to have drifted from neighbouring EEZs less than one month prior to fishing. dFADs typically transited multiple EEZs, with a median of 4 and a maximum of 14, when assuming a drift-time of six months. Moreover, between 4 and 22% of dFAD sets made in the WCPO were estimated to have originated from the Eastern Pacific Ocean, depending on drift-time. We examine our results in the context of the improved management and assessment of dFAD fisheries, providing a methodology to estimated relative dFAD density over historical periods to support analyses of catch and effort. The sensitivity of these estimates to hydrodynamic models, including the proposed SKIM doppler radar altimetry method, is discussed.

Introduction

In the Western and Central Pacific Ocean (WCPO), purse seine fisheries account for over 60% of all catch in the largest tuna fishery in the world (Williams and Reid 2018). This fishery represents a key source of financial income and employment at the national level for tropical Pacific island countries, with revenue from fishing access agreements providing up to 98% of the national government revenue for some (FFA 2017). The eight Pacific island countries making up the Parties to the Nauru Agreement (PNA) have formed a sub-regional arrangement with Tokelau to manage the purse seine fishery within their Exclusive Economic Zones (EEZs), through the PNA purse seine Vessel Day Scheme. Understanding the dynamics of this fishery and the connectivity between their EEZs, is therefore important for their management.

Worldwide, the use of drifting Fish Aggregating Devices (dFADs) by tuna purse seine fisheries has increased dramatically over previous decades, with patterns of use varying depending on region (Fonteneau *et al* 2013, Maufroy *et al* 2016). In the WCPO, this mode of fishing is now a major method for industrial fleets, and dFADs are deployed in the tens of thousands each year (Gershman *et al* 2015, Escalle *et al* 2018b). Simple dFADs may consist of a bamboo raft, attached to a hanging, sub-surface appendage acting as a drogue as they drift with currents. This appendage structure reduces drift speed and appears to increase the attractive power of the device, although the mechanisms driving the aggregation of tunas and other pelagic species around floating objects is not fully understood (Bromhead *et al* 2003). Generally, dFADs are left to drift for 3–4 weeks before any fishing takes place around them, a period during which they begin to colonise and aggregate both target and non-target species (Moreno *et al* 2007, Orue *et al* 2019). Then dFADs may be set on several times over the proceeding months, with an average lifetime of 6 months in the WCPO (Escalle *et al* 2018a). Electronic tagging experiments have shown that tropical tunas associate with floating objects over periods of days to weeks (Schaefer and Fuller 2013, Forget *et al* 2015, Scutt Phillips *et al* 2017), allowing a greater chance of successful catches when fish are aggregated near the surface in the local vicinity of dFADs, the positions of which are known to fishers. In modern purse seine fisheries, custom made, satellite-tracked dFADs are equipped with echo-sounders allowing fishers to monitor nearby aggregations (Lopez *et al* 2014). Thus, fishing on both natural and artificial floating objects has been used for decades to increase the probability of purse seiners locating tuna schools, as well as improving catchability through a larger catch-per-set compared to 'free-swimming' schools (Leroy *et al* 2013).

Industrial fishing on dFADs results in catches comprised mostly of skipjack (70% of the purse seine catch in the WCPO), as well as small yellowfin and bigeye tuna (Williams and Reid 2018). In the WCPO, the technology underpins a significant proportion of catch in the region, with 27% of purse seine sets made on dFADs during 2017 (Williams and Reid 2018). The large purse seine fleet comprises more than 250 domestic and distant water fishing nation vessels, with a pattern of dFAD use that varies depending on the fishing strategy of each fleet or fishing company. 100% purse seine observer coverage in the region has complemented captains' logsheet declarations by adding details on dFADs structure and deployment locations. However, inconsistencies remain regarding how and when these data are collected (Escalle *et al* 2017), with the many dFAD deployments not recorded by observers (Escalle *et al* 2018b). Hence, while data on the number and location of dFAD fishing events are well documented in both datasets, the operational dynamics of deployment, drift trajectories and ultimate fate of these objects remains largely unclear. In turn, untangling the influences of technological fishing improvements and environmental effects is challenging, yet necessary to understand the potentially increasing impact of fishing on tuna populations within the WCPO.

The use of dFADs is associated with several potentially negative ecosystem effects, only some of which can presently be mitigated against (Leroy *et al* 2013). These include higher bycatch of non-target species compared to purse seine sets on 'free schools' of tuna, relatively greater catch of undesirable size-classes of the target species (such as small yellowfin and bigeye tuna), as well as increased marine pollution, beaching, and ghost-fishing (Dagorn *et al* 2013). Pacific island countries and territories (PICTs) have raised concerns over an increasing incidence of FADs beaching on shores and coral reefs over recent years, and the source of these events is of increasing interest. However, it is perhaps the lack of knowledge on the relationship between effort and catch in purse seine dFAD fisheries that is of most concern. Sustainable fisheries management requires the effective assessment of fish stocks, which involves informed and accurate measures of fishing effort. A better understanding of the effective 'effort' of dFAD fisheries requires data on the ambient number and distribution of active dFADs in a region. Indeed, the general increase of dFADs deployed across the Pacific Ocean has raised concerns regarding the effect on catch-per-unit-effort (CPUE), through potential tuna school fragmentation and lower occurrence of free schools (Sempo *et al* 2013, Escalle *et al* 2018b).

Drogued floating objects such as dFADs are largely driven by surface ocean currents (Imzilen *et al* 2019). The upper ocean circulation can be separated into (1) near surface Ekman flow in the upper tens of meters, directly generated by surface winds; (2) large-scale geostrophic currents, which extend to hundreds of meters depth; (3) mesoscale variability, including ocean eddies that act to mix the ocean and (4) Stokes flow by surface waves at the absolute surface of the ocean. In the central and eastern tropical Pacific, Ekman currents act to push floats away from the equator. The slow but pervasive large-scale flow is predominantly eastwards across the tropical basin, made up of the South and North Equatorial Currents. Exceptions to this are the narrow eastward counter currents that straddle the equator just below the Intertropical Convergence Zone and the South Pacific Convergence Zone. In the far western parts of the tropical basin, much narrower (around 100 km) and more rapid (around 1 m s^{-1}) boundary currents move water, equatorward. While most current persist through the year, seasonal and ENSO-related variations in strength can be large.

The passive tracks of real dFADs moved by these ocean current systems have only recently been available to scientists in some areas (e.g. Fonteneau *et al* 2013, Escalle *et al* 2018a). Such tracking data corresponds to positions of satellite buoys deployed on one or several dFADs following appropriation processes, but only when satellite buoys are activated and reporting their positions. Mandatory submission of quality dFAD trajectory data to regional fisheries management organisations (RFMOs) as part of management plans is presently being discussed. However, until such data are consistently available, and to account for unmonitored, temporarily

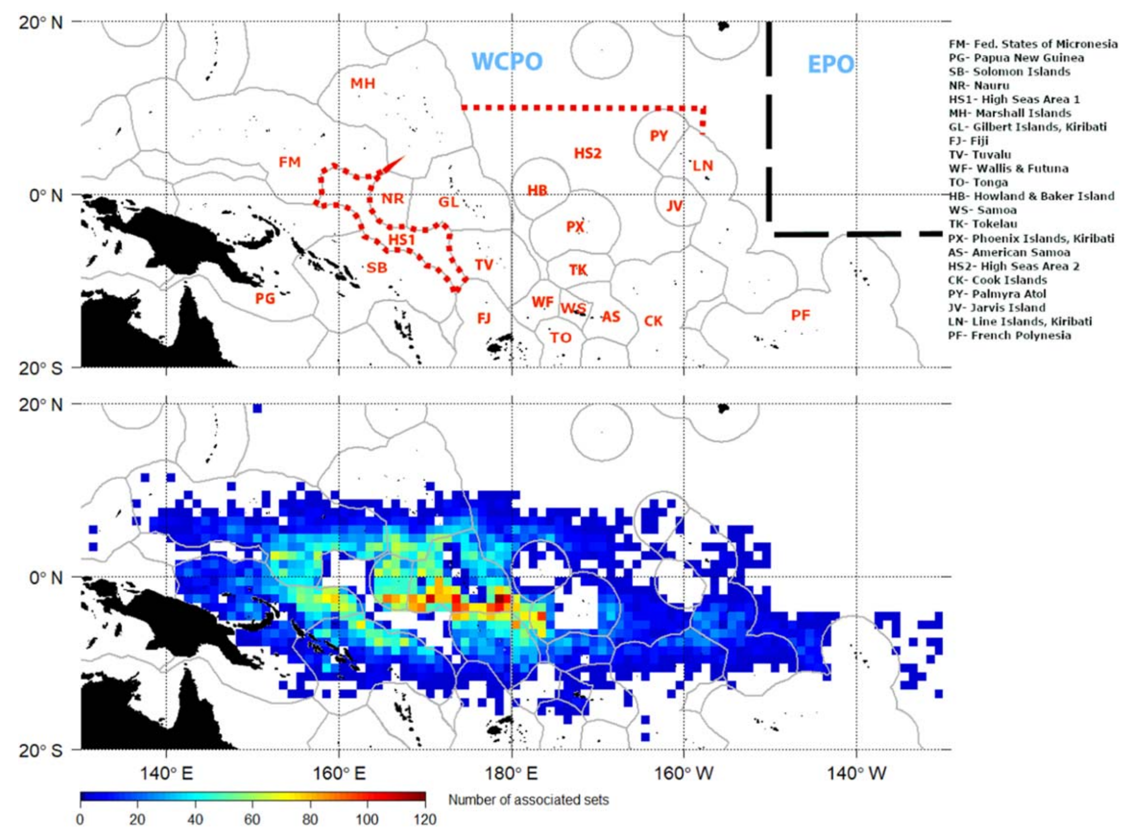


Figure 1. Map of the Pacific Ocean, with territorial exclusive economic zones (grey, solid), high seas areas (red, dotted), and Western and Central Pacific Ocean (WCPO) and Eastern Pacific Ocean (EPO) convention areas (black, dashed) marked (top panel). Density of associated sets recorded in logsheets during 2016–2017 are shown at 1° resolution (bottom panel).

deactivated, or abandoned dFADs, as well as for those historical periods during which detailed dFAD data are unlikely to ever be available, estimating the spatiotemporal dynamics of dFADs deployed in tropical areas is an important step in informing sustainable management of tropical tuna fisheries.

In the absence of trajectory data from large scale and long-term drifter deployments, Lagrangian simulation models of virtual dFADs can be useful to estimate the probable pathways of passively drifting objects through time (van Sebille *et al* 2018). These models have been used to track ocean debris (Lebreton *et al* 2012), ocean animals and larvae (Cetina-Heredia *et al* 2015, Scutt Phillips *et al* 2018) and even the potential course of dFADs in the Indian and Atlantic Oceans (Imzilen *et al* 2016, Imzilen *et al* 2019). Here, we use recent data from purse seine vessels fishing on dFADs and naturally floating logs in the WCPO to seed a Lagrangian, passively-drifting particle simulation model, under differing physical ocean flow scenarios. The results of these simulations are used to estimate potential dFAD density and connectivity between regions of the tropical Pacific, and demonstrate a method to estimate dFAD density in areas, or during periods, for which observed trajectories are either not available or do not exist. We discuss the benefits of modelling floating object dynamics using ocean flow models based on more accurate measures of equatorial currents, and the management implications of our results.

Methods

Fisheries data

Anonymised WCPO purse seine vessel fishing data for a recent two-year period of 2016–2017 are available via the Pacific Community's Oceanic Fisheries Program (SPC-OFP). The known locations of floating objects that were fished on were identified by extracting every purse seine fishing set that was associated with either a dFAD or natural floating 'log' (set types were: 90% dFADs and 10% natural logs) during this period (N = 21,454, figure 1). While on-board, scientific observers sometimes also record the characteristics of the dFADs (e.g. depth of appendages), this information remains limited (i.e. around 20% of associated sets, Escalle *et al* 2017) and so the fishery logbook data we use here represent the most complete information available on set time and location for the period studied. These locations were used to seed particles in a Lagrangian simulation to estimate their drift trajectories backwards through time, prior to each observed fishing event.

Table 1. Summary of the three ocean forcing scenarios used in our study.

Scenario	Depth	Details
CMEMS-appendage, 'Baseline'	Averaged surface to 50 m depth	Flow experienced by dFADs with a 50 m appendage
CMEMS-surface	Surface	Flow experienced by natural floating objects or logs
SKIMulator-surface	Surface	Rendering of how SKIM would observe surface flow experienced by natural floating objects or logs, based on CMEMS-surface currents

Lagrangian simulation model and flow field data sets

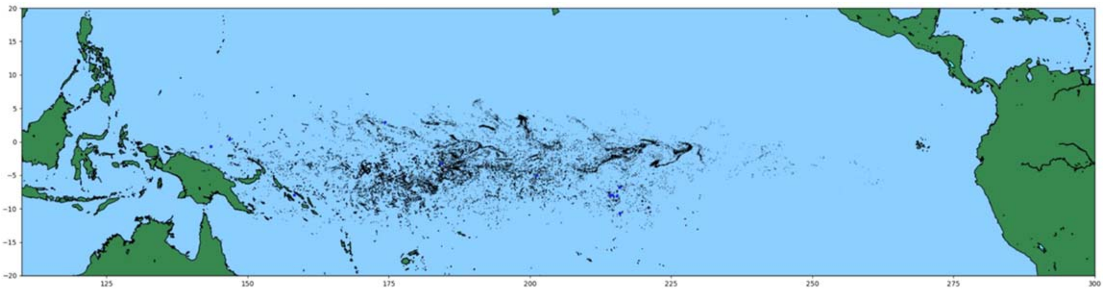
Using the *Parcels* Lagrangian simulation modelling framework (Lange and van Sebille 2017), we seeded particles (representing virtual dFADs) at the time and location of each observed purse seine associated set (figure 1). These particles were then advected backwards in time, using flow fields under three scenarios based on different ocean circulation data sets (see below). The advection was computed using a fourth-order Runge–Kutta integration with a timestep of 10 min. Parcels uses bilinear interpolation in space and linear interpolation in time between the model flow snapshots. The positions of the particles were recorded every five days over a period of six months prior to the set (average lifetime of buoys deployed on dFADs in the WCPO, Escalle *et al* 2018a). As a buoy may be re-deployed several times on separate dFADs (Escalle *et al* 2018a), actual buoy and dFAD drift durations may be quite different. However, the buoy lifetime remains the only available proxy of dFAD drift duration, given that dFADs themselves cannot be followed at present. For each fishing event, ten particles were released. Small random displacements were added to the position of particles at each time step, using a Brownian Motion model with a diffusivity constant of 10 $m^2 s^{-1}$ (Okubo 1971, Van Sebille *et al* 2018), to account for small scale variability not captured in the current forcing. The resulting spread of particles backward through time captured the uncertainty in the floating object trajectory prior to the observed set. Backward-tracked particles were prevented from stranding on land by applying an extra flow away from all coastlines following Delandmeter and van Sebille (2019). The Python code for all simulations is available at https://github.com/OceanParcels/SKIM_dFADtracking.

Three simulations using different ocean forcing datasets were implemented (table 1), all based on the Copernicus Marine Environmental Monitoring Service (CMEMS) fine-resolution global forecasting model at 1/12° spatial resolution and available at daily temporal resolution. CMEMS is a state-of-the-art ocean model, and assimilates satellite data of sea surface temperature, sea wave height, sea level and sea ice, as well as *in situ* temperature and salinity profiles. First, as a baseline scenario, we used CMEMS to provide the horizontal velocities averaged over the upper 50 m to simulate the movement of particles seeded from all dFAD set locations, and on which we focus our analyses of connectivity (animation 1). 50 m corresponded to the median depth of dFAD appendage recorded by observers in the WCPO (Escalle *et al* 2017). A second simulation was then run using only CMEMS surface current velocities to seed particles from log set locations. Finally, a third sensitivity simulation was carried out in which these particles representing virtual logs were subject to a flow field at a resolution that would be measured by the proposed SKIM satellite mission. SKIM is one of two candidate missions for the European Space Agency's (ESA) Earth Explorer 9 satellite. Its aim is to measure surface currents and waves directly from space, using a doppler radar altimetry method (Ardhuin *et al* 2018). Since SKIM is not yet operational, we use a version of the CMEMS-surface scenario data, but where the data is sampled at the spatial and temporal resolution that SKIM would have, and then interpolated with the algorithms that SKIM L3a would use (developed by Collecte Localisation Satellite).

Simulated floating objects

dFADs are usually deployed and left to drift for at least 1 month before being set on by vessels (Moreno *et al* 2007, Leroy *et al* 2013), with an average lifetime of around 6 months in the WCPO (Escalle *et al* 2018a). After a set is complete, dFADs may be retrieved to be redeployed elsewhere or the device may be left to continue drifting. Unfortunately, this information on dFAD retrieval is currently not recorded consistently in either logbook nor observer data. In this study the assumption was made that, prior to each dFAD or log set, the floating object had drifted for a period of up to six months. We also assumed that, following the observed fishing event, the floating object was removed from the ocean. Below, we provide floating object density maps by calculating the total number of particles present in each $1 \times 1°$ grid cell at each 5-day timestep, and dividing this value by the number of particles used to represent each floating object (here, 10 particles per fishing event). As the actual drift-time of each floating object prior to fishing is unknown, two approaches were examined: one where all floating objects were assumed to have drifted for 6 months prior to the fishing event date (i.e. the object was fished 6 months after being 'deployed'), the other where the in-water duration prior to the set date was assumed to be less than 6 months (i.e. the object was fished between 0 and 6 months after being deployed). For the latter approach, we used a weighted density calculation that was a function of drift time for each particle. This represented the probability of a particle being in the water decreasing non-linearly with time, until reaching 0 at 6 months prior to set time. This gave high weights to positions one month prior to the observed set time, dropping non-linearly to 0.5 by 130 days, and then zero at 180 days (supplementary figure S1, equation S1 is available online at stacks.iop.org/ERC/1/055001/mmedia).

To examine connectivity, retention time and throughput of dFADs, the locations of all particles were classified into regions during the potential 6-month drift-time prior to set location. These regions corresponded to either the EEZ of a PICT in the WCPO, one of two WCPO high seas areas in the equatorial zone (see figure 1), the wider high seas area, or the Eastern Pacific Ocean (EPO). Retention time and throughput of dFADs prior to set location was calculated for each region as the sum of time spent in that region by all dFADs, and the number of unique dFADs used in that sum, respectively. Connectivity matrices were constructed to show, for all observed associated sets in each region, the probability of origin region for that floating object, calculated over three drift-time bins of less than 1 month, 1 to 3 months, and 3 to 6 months. When constructing connectivity matrices, we used no weighting function of drift time. Those EEZs that had less than 10 recorded dFAD sets were removed as associated set locations (rows) from the connectivity matrices below, and those that showed negligible connectivity of less than 5% as origin EEZs (columns) across all set location regions were also removed.



Animation 1. Daily movements of simulated particles representing dFADs under our baseline scenario. The trajectories of all 10 particles per observed set are plotted. Particle transparency is weighted by drift-time, and particle groups flash blue when they come together at the location of the observed set.

Results

Density

The estimated density of simulated dFADs, under the assumptions of our baseline scenario, shows the highest density centred in the western equatorial region, principally across the EEZs of the Gilbert Islands, Tuvalu, Howland & Baker and the Phoenix Islands (figure 2(a)). The high seas region between these EEZs (high seas area 2) is also estimated to contain a high density of dFADs. This distribution extended to moderate densities present both north and west of this high dFAD density area, as far as the EEZs of the Solomon Islands in the west, the Federated States of Micronesia in the north-west, and towards the edge of our defined high seas area 2 to the north. Density of dFADs originating from specific locations in the EPO appeared generally low. A slightly increased density extended from the core area of high density to the east along the southern edge of the equator through the EEZ of the Line Islands, which was stronger when assuming an equally weighted 6-month drift-time (figure 2(c)). The eastern limits of estimated dFAD origins begin from around Clipperton Island north of the equator to the Galapagos Islands in the south, although the probability that any dFAD set originated from a single cell east of 220 °E was low.

When examining those purse seine associated sets that corresponded to surface-drifting logs, estimated density reflected the bias in location of these sets in our fisheries data, being more common in the western Pacific around Papua New Guinea and the Solomon Islands (figure 2(b)). The highest estimated density of logs that were ultimately fished on occurred around the Bismarck Sea area, with most of the density concentrated along the equatorial zone.

dFAD retention and throughput

The distribution of time spent by transiting dFADs in each EEZ and high sea region, where at least 10% of all simulated dFADs passed through, was calculated (figure 3). Unsurprisingly, the region that had the longest median time spent by dFADs was the large area comprising the EPO (60 days). The single EEZ with the highest median retention time was Tuvalu (35 days). These were followed by the Solomon Islands and high seas area 2 (30 days). The actual proportion of all simulated dFADs passing through these regions varied considerably.

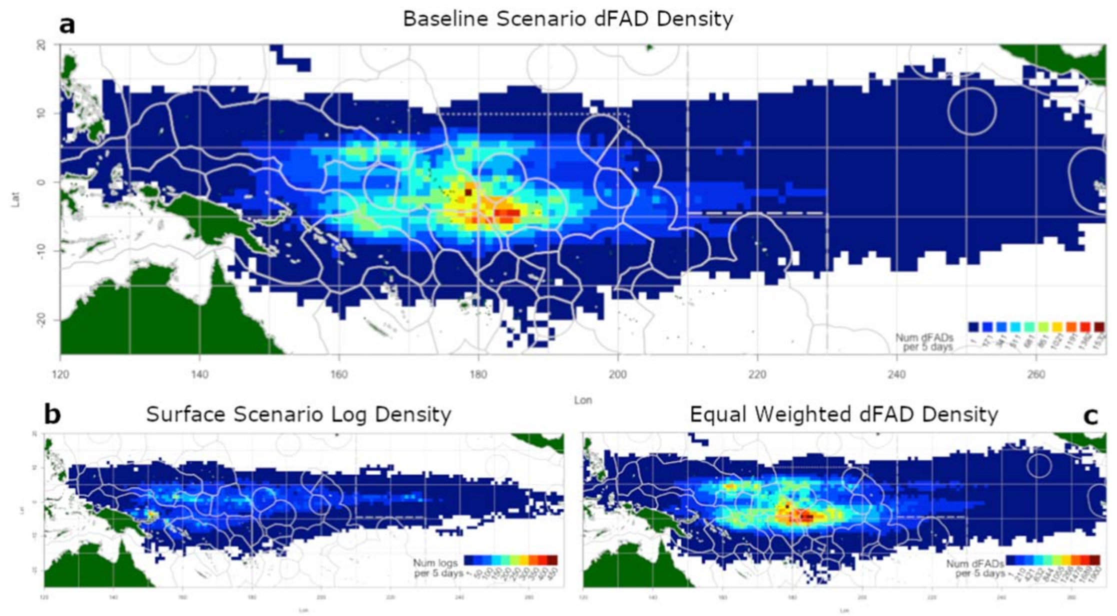


Figure 2. (a) Total simulated dFAD density over 2016–2017, from our baseline scenario assuming 50m-averaged CMEMS forcing. Density contributions from each particle are weighted with a square power law decay function of drift-time. (b) Total simulated natural floating 'log' density over 2016–2017, from our CMEMS surface forcing only scenario, with density contributions from each particle weighted equally over the entire 6-month maximum drift-time. (c) Simulated dFAD density from our baseline scenario, also with equal, 6-month weighting.

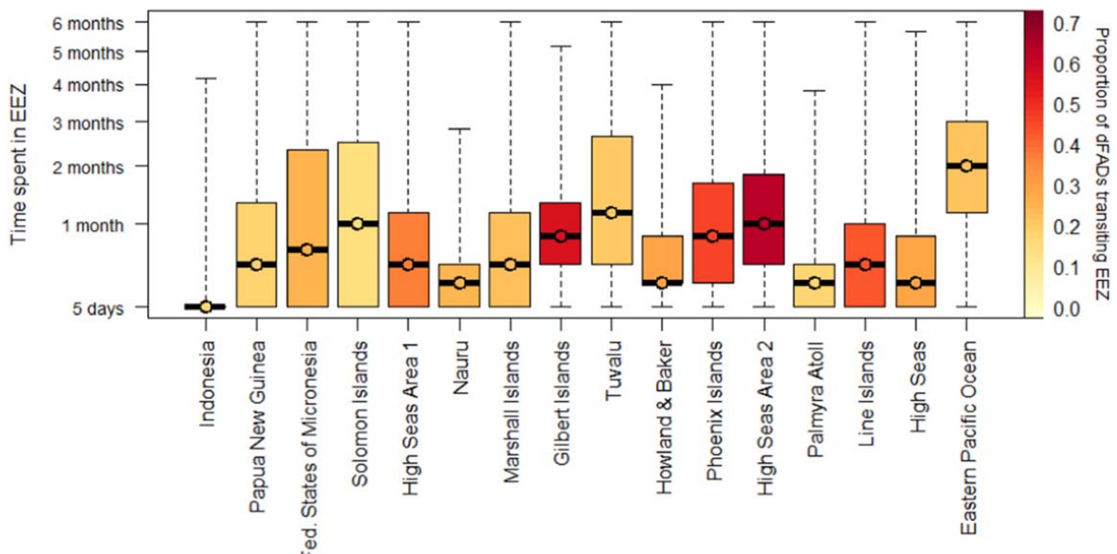


Figure 3. Boxplot showing distribution of time spent by dFADs in each EEZs, assuming a 6-month drift-time. Results are shown only for those EEZs through which at least 10% of all simulated dFADs transited for at least one day, with boxes coloured relative to that proportion.

High seas area 2, which is the large zone in the central equatorial Pacific, had the highest throughput of dFADs (62%), whilst Vanuatu had the least number of transiting dFADs (0.1%). The separate EEZs of Kiribati experienced very high proportions of transiting dFADs, spread across the Gilbert Islands (55%), the Phoenix Islands (45%), and the Line Islands (43%), with relatively high retention times for two first EEZs. Despite the generally high retention time of dFADs, Tuvalu and the Solomon Islands had lower throughput of transiting dFADs, with 21% and 15% of all dFADs, respectively. Of note is the large variability in retention time by EEZ for the more western EEZs (Papua New Guinea, Federated States of Micronesia and the Solomon Islands), with many dFADs spending less than one week in these areas. Finally, 22% of all simulated dFADs drifted through the EPO before being set on in the WCPO.

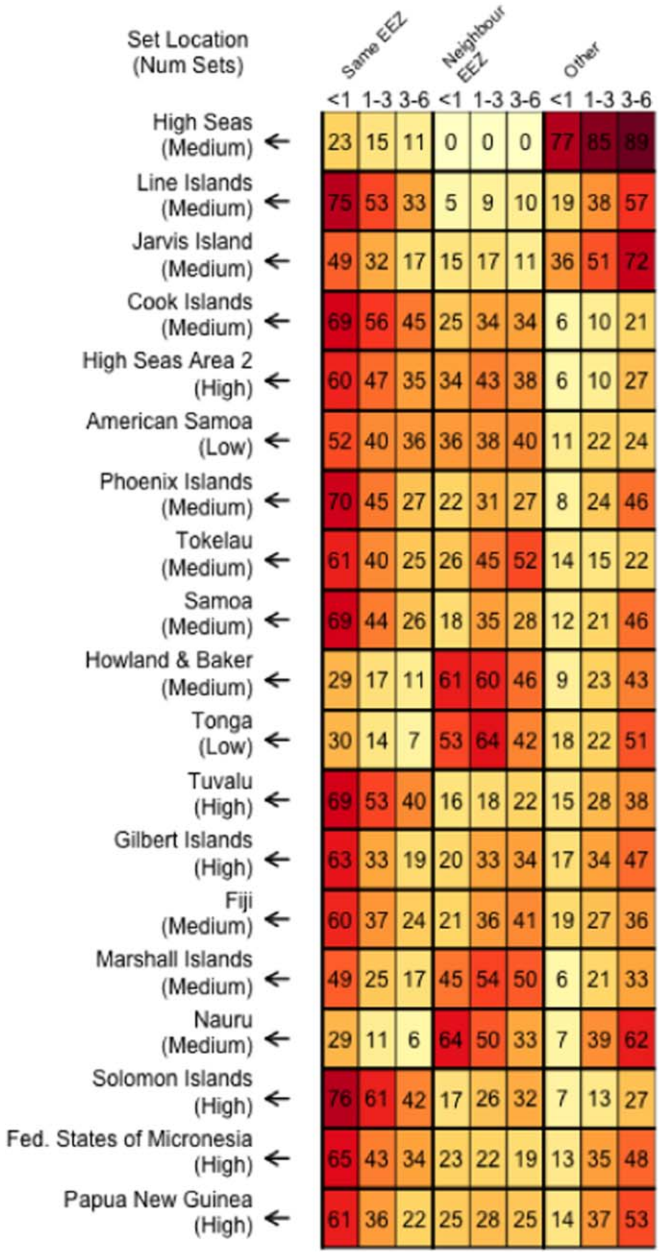


Figure 4. Connectivity matrix between EEZ location of logbook recorded dFAD sets (rows), and estimated probability of source locations (columns) under our baseline scenario, grouped as the same EEZ as the set location, a neighbouring EEZ, or a further EEZ/high seas location. Quartile-bin of number of associated sets during our study period are shown in brackets for each EEZ.

Connectivity

The connectivity of simulated dFADs between EEZs showed patterns that broadly correspond to the generally east to west movement of near-surface currents in the equatorial Pacific region (EEZ specific connectivity is shown in the supplementary material, figure S2). As expected for the majority of regions, when a dFAD had only been drifting for less than one month there was a high probability that it originated from the same EEZ where the corresponded purse seine set was made (figure 4). This probability decreased with longer drift-times as the likelihood of dFADs having arrived from nearby EEZs or further locations to the east increased. A notable exception to this includes dFADs set on in the EEZ of Nauru, where even one month prior to observed dFAD sets in region, there was a greater probability of simulated dFADs arriving from the neighbouring Gilbert Islands. The EEZs of Tonga and Howland & Baker Islands also had a lower immediate connectivity within their own region for short drift-times, with the majority of dFADs arriving from Wallis & Futuna for the former, and the Phoenix islands for the latter. Conversely, the Cook Islands, Tuvalu, and the Solomon Islands exhibit the strongest connectivity to their own EEZs, even when assuming dFADs had drifted up to 6 months prior to purse seine sets being made.

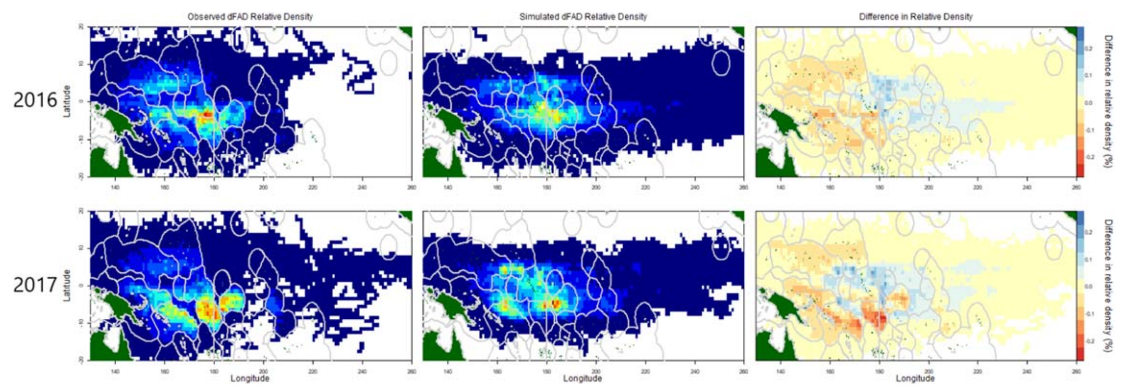


Figure 5. Comparison of adapted figure from Escalle *et al* (2018a) showing standardised dFAD density from observed trajectories (left), simulated dFAD relative density from this study (middle), and absolute percentage difference between the two (right), shown separated here by year (2016 top, 2017 bottom). Greater simulated density is shown in blue, greater observed density in red.

Summarising across all virtual dFAD particles, the number of EEZs traversed, excluding high seas areas, was normally distributed. When assuming a full 6-month drift-time, 4% of simulated dFADs remained outside of any WCPO EEZ, while 17% passed through 4 different EEZs, which was also the median number. 65% of dFADs traversed at least 4 separate EEZs, up to a maximum of 14. When considering only the final month before the observed fishing set was made, the median number of EEZs traversed was only 1, for 48% of dFADs. 2 EEZs were traversed by 28% of dFADs, with 16% passing through 3 or more during their final month of drifting, up to a maximum of 6. Considering any time spent traversing the EPO, 4% of dFADs drifted from this region during their final month prior to fishing sets being made. This increased to 9% and 22% when considering drift-times of up to 3 and 6 months, respectively.

Discussion

Comparison with observed dFAD trajectories

Our estimates of historical dFAD drift trajectories provide a number of new perspectives on previously unknown dynamics. The availability of dFAD drift trajectories in the WCPO is a recent development, representing only a portion of all dFAD trajectories in the region, with a dataset of over 26 000 active dFADs being made available by fishing companies operating in the fishing grounds of the PNA (Escalle *et al* 2018a). This dataset has provided important insights into the dynamics of dFAD use at industrial scales, but does not yet give a complete picture of these dynamics in the region. Firstly, the data represent only a subset of active dFADs in the WCPO (Gershman *et al* 2015, Escalle *et al* 2018b). Second, the dataset contains gaps due to (i) active removal of certain trajectory sections before submission (e.g. outside certain EEZs); (ii) transmission frequencies change; (iii) dFADs switched to ‘sleep’ mode during certain periods (e.g. during the annual FAD-closure period around July-October); and (iv) deactivation of dFADs that drift away from core fishing areas. Our study provides a way to fill these gaps using observed fishing set information combined with drift trajectories of virtual dFADs. Here, we have simulated 191 470 particles that estimate the pathways of over 19 000 dFADs in the WCPO. This likely represents between 22.2 to 40.1% of the estimated number of active buoys (i.e. a proxy for dFADs, although the same dFAD may have had several buoys and may be set on several times) used in the region during the same period (Escalle *et al* 2018b).

Comparing our relative, simulated dFAD density with standardised density from an observed dataset of dFAD trajectories over the same period (Escalle *et al* 2018a) showed clear similarities (figure 5). In particular, the core simulated high dFAD density area, across the EEZs of Tuvalu, and the Gilbert and Phoenix Islands, as well as higher densities in the Solomon Islands EEZ during 2017, is similar to the observed dFAD density in the region. Several differences can also be noted, highlighting areas where the simulations under- or overestimate dFAD density. These results suggest a considerably higher floating object density in the Howland and Baker Island EEZ, the northern Gilbert Islands and the eastern high seas areas compared to observed densities. This difference is likely to be the result of the observed trajectory data being modified prior to being made available to scientists, with transmissions from some areas of the WCPO removed (Escalle *et al* 2018a). Of interest is a large underestimation of dFAD density in the EEZ of Tuvalu during 2017 in the results of our simulations, an area within the PNA fishing ground where observed dFAD tracking data is unlikely to have been removed prior to submission for analyses. The percentage of dFAD sets made in Tuvalu fell from 8.1% of all sets to 4.4% between 2016 to 2017. It appears that there was a high density of dFADs in this region during 2017, a large proportion of

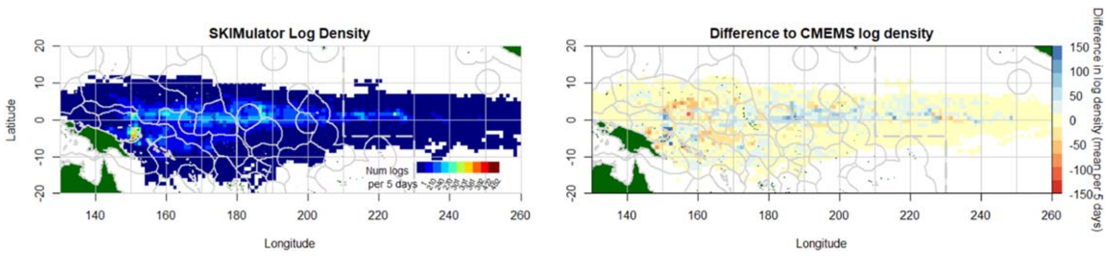


Figure 6. Simulated log densities under SKIMulator-surface flow field forcing scenario (left), with comparison to those densities estimated by the CMEMS surface log scenario (figure 2(b)) shown in absolute differences where blue indicates greater density estimated by the SKIMulator scenario, and red, lower density (right).

which were never set on by purse seiners in this EEZ that year, and therefore do not manifest in the density estimated by our simulation approach.

General discrepancies in dFAD densities between our baseline scenario and observed dFAD density show relatively lower density in western areas such as Papua New Guinea and the Federated States of Micronesia, and relatively higher densities in the western and central high seas areas. It is unclear whether this is a result of inaccuracies in our ocean current flow fields, bias in the subset of dFADs present in the dFAD tracking data, or our assumption that dFADs are removed from the water at time of setting. This latter point will underestimate those dFADs that are set on within the core dFAD fishing areas, and subsequently left to drift further west, as we do not simulate trajectories post-set in these simulation experiments. Given the lack of information regarding the dFAD drift duration, the average lifetime of a buoy in the WCPO (i.e. 6 months) has been used as the simulated particle duration. The large variability in buoy lifetime, and likely dFAD drift duration should be kept in mind, and may also influence the results of this study. While there is a lack of available information regarding FAD densities worldwide, the WCPO is the only ocean basin where, although incomplete, large-scale dFAD density have been compiled (Escalle *et al* 2018a). In such context, the method of combining the know position of dFADs with Lagrangian simulation used in this study could be used in different oceans and over historical periods to construct a more complete picture this density.

Sensitivity to ocean products

While the spatial density of virtual 'log' particles is affected by a western bias in set locations, as these objects will largely originate from Papua New Guinea and the Solomon Islands, using only surface currents to advect these particles gives rise to significantly different estimates of distributions of these objects compared to 50 m depth-averaged forcing for dFADs. Simulations using only surface currents suggest much greater floating density around the equator compared to the baseline scenario. It is clear that if the dFADs were subject to surface velocities, the average density would be more enhanced along the equator. This is explained by the fact that wind driven equatorial divergence is confined to the surface ocean, and so tracking backwards in time we see an enhanced equatorial convergence of particles.

In order to keep simulations simple, and considering that the depth of submerged appendages is only available for around 20% of the associated sets in the observer data, an average length of 50 m was assumed for dFAD appendages. However, Imzilen *et al* (2019) demonstrated a difference in drifting behaviour between dFADs drogued at different depth. In particular, it was found that dFADs in the Atlantic Ocean, up to 80 m deep, drifted slower than drifters used in oceanographic experiments, while those from the Indian Ocean (50–60 m) had similar drift pattern. In the WCPO, while the median appendage depth is 50 m, it appears that dFADs may be generally slightly deeper in the West (50–70 m) compared to the East (30–60 m) (Escalle *et al* 2017), and this could possibly influence the drift behavior simulated in this study.

The ocean models used to force the trajectories of floating objects assimilate equatorial currents, which are poorly observed. This is because satellite-altimetry-based data products cannot be used for flow calculations near the equator, as the Coriolis parameter approaches zero and the geostrophic balance breaks down. The recently proposed SKIM satellite (Ardhuin *et al* 2018) could improve equatorial velocity estimates, measuring surface flow directly from Doppler shifts of active radar signals. Figure 6 shows our estimated density of logs based on velocity data from the SKIMulator scenario, compared to the CMEMS-surface flow results from figure 2(b). This model takes the CMEMS-surface flow and samples it as the SKIM satellite would, based on its orbit. It then uses the optimal interpolation routines that will be used for the real SKIM post-processing in order to render the surface flow (https://git.oceandatalab.com/skim/skimulator). The CMEMs-surface and SKIMulator simulation densities are similar, however SKIMulator log densities are more consistently elevated along the equator, with a more diffuse distribution throughout the Bismarck Sea and lower density in parts of the

Federated States of Micronesia. This suggests that the SKIM sampling resolution would be sufficient to accurately measure tropical ocean surface flow, thereby improving the overall flow fields affecting floating items such as dFADs, natural floating objects and marine pollution. Furthermore, it may even be possible to parameterise deeper flow fields using empirical, model-derived relations between surface currents, wave height and the depth-averaged flow.

Management implications

The current lack of understanding of dFAD dynamics over the last 20 years is of key concern for the management of sustainable tropical tuna fisheries into the future. In the case of WCPO tropical tunas, the introduction of dFAD-use as common practice appears to have supported increased purse seine catch, with further contributions from subsequent technological advancements (Lopez *et al* 2014). These developments have likely increased the fishing 'power' of vessels, and hence will influence CPUE metrics such as catch per day spent searching or fishing in ways that are not currently understood. Here, we have demonstrated an approach to estimate historical dFAD dynamics. While our method only accounts for floating objects that ultimately resulted in purse seine sets, and may be biased by dFADs set on multiple times during a single drift trajectory, it nevertheless provides a standard measure of the, until now, unknown distribution of fished floating objects across the whole WCPO. Despite the recent availability of dFAD trajectory data for scientific analysis (Maufroy *et al* 2015, Escalle *et al* 2018a), our approach is a pragmatic one given the necessity of understanding dFAD dynamics over many years, before the existence of such datasets, which themselves remain incomplete. In addition, using Lagrangian simulation we have been able to shed light on the 'gaps' in this trajectory dataset caused by lack of full data availability or low transmission frequencies by real dFADs outside main dFAD fishing areas and periods (i.e. dFAD closures). In particular, our simulations suggest much higher densities of dFADs in high seas regions than is observed in tracking data, almost certainly due to these sections of trajectories not being made available for scientific analysis.

Management of the impact of dFAD fishing events on tuna stocks has been through the prohibition on the deployment, servicing or setting on FADs during specific seasons and in specific areas of the WCPO. The Western and Central Pacific Fisheries Commission Conservation and Management Measure (CMM) 2018-01 specifies a three-month closure on dFAD fishing between the 1st July and 30th September in both EEZs and on the high seas, with an additional two-month closure on the high seas in either April-May or November-December. Consideration of the movement of dFADs across these periods, when existing deployed dFADs are allowed to drift, can therefore inform on the wider environmental impacts of beaching and the loss of dFADs from productive fishing grounds.

Our analysis of connectivity highlights the retention of large proportions of dFADs within EEZs over short to medium timescales. In particular, the EEZ of Tuvalu showed particularly high retention times for simulated dFADs, second only to those estimated for the entire region of the EPO. However, connectivity was high for the majority of PICTs, and any country-specific management measures regarding dFADs fished upon within their area of national jurisdiction would need to extend principally to their own, but also to neighbouring EEZs when dFADs have drifted less than three months prior to fishing. Furthermore, those neighbouring EEZs are usually located to the East and North for the greater number of EEZs in the southern hemisphere. All three EEZ regions of Kiribati had a high throughput of simulated dFADs when compared to any other region, with more than half of all dFADs set on during 2016 and 2017 estimated to have drifted through the surrounding high seas region (high seas area 2, figures 1, 3). At longer drift-times, dFAD connectivity varies on a country-by-country basis: detailed connectivity matrices (supplementary material figure S2) suggest that 22% of dFADs set upon in the WCPO could potentially originate from the separate convention area of the EPO, if drifting for 6 months prior to fishing. Pacific Islands with relatively smaller EEZs tend to be the exception to this rule, where connectivity is more weighted to neighbouring territories, even over short drift-times (e.g. Nauru).

The EEZ dFAD retention times we have calculated here demonstrate an alternative spatial measure of fishing effort to days fishing or number of sets made. Assuming that the number of dFADs in an area is related to fishing strategy and success, then a method of combining simulated dFAD trajectories with available dFAD position data may provide a standardised density covariate for understanding changes in catchability and CPUE in purse seine fleets targeting tuna (Lopez *et al* 2015, Tidd *et al* 2017). The access to currently incomplete dFAD tracking data has already indicated the potential influence of high dFAD densities to CPUE in these fisheries (Escalle *et al* 2018b).

Conclusion

In this study, we have outlined an approach to estimate the dynamics and connectivity of dFADs by combining known positions during fishing operations and Lagrangian simulations. Our results provide further evidence that EEZs such as the Solomon Islands and Tuvalu are vulnerable to long dFAD retention times and the potential associated beaching (Escalle et al 2018a). High throughput of floating objects, driven by strong equatorial currents, through the EEZs of Kiribati indicates the strong connectivity of dFADs via this country's territorial waters to the wider WCPO region. This work also highlights the very high densities of dFADs likely to be present in high seas areas, where there is at present a critical lack of available trajectory data for scientific analysis. More broadly, our results have provided a greater understanding of the connectivity of typical dFAD drift patterns, with implications for the effective design of mitigation measures against beaching (Escalle et al 2018a), the identification of unfavourable trajectories for dFAD recovery programmes (Zudaire et al 2018), and spatial considerations for potential dFAD-closures (Kaplan et al 2014).

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