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Is it all about the haul? Pelagic false killer whale interactions with longline fisheries in the central North Pacific

David Anderson[a], Robin W. Baird[a], Amanda L. Bradford[b], Erin M. Oleson[b]

[a]Cascadia Research Collective, 218½ West 4th Avenue, Olympia, WA, 98501, USA

[b]Pacific Islands Fisheries Science Center, NMFS, NOAA, 1845 Wasp Boulevard, Building 176, Honolulu, HI 96818, USA

Corresponding author: David Anderson danderson@cascadiaresearch.org

Email addresses: danderson@cascadiaresearch.org (D. Anderson), rwbaird@cascadiaresearch.org (R.W. Baird), amanda.bradford@noaa.gov (A. L. Bradford), erin.oleson@noaa.gov (E.M. Oleson)

ABSTRACT

Pelagic false killer whales (*Pseudorca crassidens)* are killed or seriously injured in the Hawai'i-based deep-set longline fishery more than any other cetacean, with bycatch regularly exceeding allowable levels. Telemetry data from five satellite-tagged whales (from three groups) and longline logbook entries (4,182 sets) from the Hawai'i-based longline fisheries are used to assess the range of the population and potential interactions with longline gear. A switching state-space model with a 4-hour time step was used to assess the behavior of the tagged whales. Two of the groups remained within the U.S. EEZ surrounding the Northwestern Hawaiian Islands, while one group spent 87.5% of its time in international waters to the east of the Hawaiian archipelago. Tagged whales came within 100 km of only 26 sets over the 184 days of tag data, with only two of the three groups coming within 50 km of a set. Only twice were whales (from only one group) known to approach closely enough to interact with gear, during two series of three deep-sets, with only one of the six sets recording no catch (indicating probable catch depredation). Movement towards the sets was most dramatic during the haul phase, in one case the tagged whales moved almost 100 km towards the gear in 7 hours. During one set in each of the two of the interactions, whale behavior changed to 'area restricted search' (indicative of foraging) during periods that overlapped with hauling of the gear. Overall, our results show that pelagic false killer whales spend a relatively small proportion of their time interacting with U.S. longline gear, and suggest that hauling gear may be an important cue initiating interactions.

Keywords: Bycatch; Longline fishing; Satellite tagging; Depredation; False killer whales; *Pseudorca crassidens*

1. Introduction

Fisheries bycatch, the taking and discarding of non-target species, is one of the greatest threats faced by many cetacean populations (Read, 2008), including false killer whales (*Pseudorca crassidens*) in Hawaiian waters (Carretta et al., 2017). The false killer whale is the most common species of cetacean bycaught in the Hawai‘i-based deep-set longline fishery that targets bigeye tuna (*Thunnus obesus*), with a smaller number of animals taken by the shallow-set longline fishery targeting swordfish, *Xiphias gladius* (Bradford and Forney, 2014, 2017; Forney, 2010). Bycatch of false killer whales in Hawai‘i-based longline fisheries has been recognized as a potential management and conservation issue since observer data first became available in the mid-1990s (Forney, 2004). Estimates of pelagic false killer whale bycatch based on data collected by observers of the deep-set longline fishery have exceeded allowable levels for most of the last 15 or more years (Carretta et al., 2017).

Vessels fishing in the Hawai‘i-based deep-set longline fishery deploy monofilament main lines that can be 30 to 100 km in length, with lines to floats at regular intervals of ~0.4 km, intended to maintain a fishing depth of 40 m to 400 m (Boggs and Ito, 1993; Gilman et al., 2007). Between floats there are 12-40 branch lines clipped to the main line, with a single baited hook hanging approximately 10-12 m below the main line (Bayless et al., 2017; Boggs and Ito, 1993; Gilman et al., 2007). Longlines are usually set in the morning, which takes 4-5 hours, and soaked for several hours before the haul in the afternoon though evening. Depending on the catch, hauling can take 10+ hours (Bayless et al., 2017). False killer whales are known to approach longline gear to remove both bait and hooked fish from the lines (depredation), often leaving the heads of catch attached to the hook (Bayless et al., 2017; Thode et al., 2016).

Interactions with shallow-set longlines also occur, but at much lower rates, and shallow-sets represent a small proportion of the total fishing effort in the two fisheries.

Based on interviews, most Hawai‘i-based captains of longline vessels believe they are just as likely to suffer depredation losses during setting or soaking phases as during hauling (TEC Inc., 2009). Longline depredation by cetaceans occurring during hauling (Gilman et al., 2006) might be a result of animals responding to the acoustic signature of the gear hauling equipment and/or the vessel travelling slowly to retrieve the line. Acoustic monitoring of the Hawai‘i-based deep-set longline fishery revealed that most acoustic detections of false killer whales were during the haul phase of operation and that the animals tended to move along the line away from the boat during the haul, moving in the same direction as the boat (Bayless et al., 2017). This monitoring also found that only 16% of the sets with acoustic detections of false killer whales had any sign of depredation as recorded by an onboard observer (Bayless et al., 2017).

In addition to the 145 vessels active in the Hawai‘i-based longline fisheries in 2017 (Pacific Islands Fisheries Science Center, 2018), fleets from other nations also operate in the central North Pacific outside the U.S. Exclusive Economic Zone (EEZ), and presumably experience both depredation from and bycatch of false killer whales. These include Japan (Uosaki et al., 2016), Taiwan (Fisheries Agency, Council of Agriculture, and Overseas Fisheries Development Council, 2017), Republic of Korea (Kim et al., 2017), China (Dai et al., 2017), and Vanuatu (Vanuatu Fisheries Department, 2015). The non-U.S. high seas longline fishery in the central Pacific is managed by the Western and Central Pacific Fisheries Commission (WCPFC). Member nations have at least a 5% observer coverage on their longline vessels and file annual reports with WCPFC, while the Hawai‘i-based fisheries have 20% observer coverage for the deep-set fleet and 100% coverage for the shallow-set fleet.

There are three stocks of false killer whales around the Hawaiian Islands, an endangered insular population around the main Hawaiian Islands, another insular population around the Northwestern Hawaiian Islands, and a pelagic population that ranges far offshore (Baird, 2016; Bradford et al., 2015). Most of the false killer whale bycatch in the Hawai‘i-based longline fisheries comes from the pelagic stock, as the fishery is excluded from nearshore areas that represent the core part of the range of the insular stocks. Pelagic false killer whales around Hawai‘i are a transboundary stock, with a range that extends outside the U.S. EEZ, and most of the observed takes by the Hawai‘i-based longline fisheries occur outside the EEZ (Bradford and Forney, 2014, 2017). The most recent abundance estimate available for pelagic false killer whales within the U.S. EEZ around the Hawaiian Islands, based on the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) shipboard line-transect survey in 2010, is 1,540 animals (CV = 0.66) (Bradford et al., 2014, 2015). There are no estimates for abundance or trends in abundance for the entire stock that includes animals outside the U.S. EEZ. To address the unsustainable bycatch of pelagic false killer whales, the U.S. National Marine Fisheries Service (NMFS) set up a Take Reduction Team, which produced a draft Take Reduction Plan (TRP) in 2010. In 2013, the final TRP was put in place in an attempt to reduce bycatch of both pelagic and insular false killer whales in the Hawai‘i-based deep-set longline fishery. The primary tool used to attempt to reduce bycatch was a gear change, effectively involving weak circle hooks and strong terminal gear (hooks with a maximum wire diameter of 4.5 mm and branchlines with a minimum diameter of 2.0 mm). The gear changes were combined with handling guidelines for the captain and crew, to put tension on the gear to allow hooked whales to straighten the hooks, as well as research recommendations to help better understand how false killer whales detect and interact with gear. A review of data available through 2017 suggests that the gear changes implemented under the TRP are not significantly reducing rates of mortality and serious injury (NMFS Pacific Islands Regional Office, unpublished), thus there is a need for additional information to inform future modifications to the TRP.

Cascadia Research Collective (CRC) and the NMFS Pacific Islands Fisheries Science Center (PIFSC) have ongoing studies of false killer whales in Hawaiian waters (Baird et al., 2008, 2013, 2015; Bradford et al., 2014, 2015, 2018). As part of these studies, satellite tags have been deployed on individuals in all three populations. Observation and tagging opportunities for pelagic false killer whales are considerably rarer than for insular individuals, but in 2013 satellite tags were deployed by CRC and PIFSC on five pelagic false killer whales in three different groups (Bradford et al., 2015). Two of the tags exceeded 100 days in duration, offering the first opportunity to examine pelagic false killer whale spatial use and interactions with longline vessels.

This paper compares satellite tag telemetry data to logbook data from the Hawaiʻi-based longline fisheries to gain a better understanding of how pelagic false killer whales interact with fisheries. These analyses looked for potential interactions between tagged false killer whales and longline sets to determine how often the whales interact with nearby vessels, the timing of the interaction compared to vessel activity, and whether the presence of the whales affected the catch. A greater understanding of the behavior of pelagic false killer whales around longline sets will help inform the efforts of the Take Reduction Team working to reduce false killer whale bycatch and injury rates in the Hawaiʻi-based longline fisheries.

2. Methods

Pelagic false killer whales were encountered in 2013 by PIFSC during a ship-based cetacean survey of the Northwestern Hawaiian Islands and by CRC during a small-boat survey for odontocetes off Hawaiʻi Island in the main Hawaiian Islands. For each group encountered, group size was estimated, individuals were photographed, and skin biopsy samples were obtained. Whales were tagged using location-only satellite tags (SPOT-5, Wildlife Computers) using the Low-Impact Minimally-Percutaneous External-electronics Transmitter (LIMPET) configuration (Andrews et al. 2008). Tagging was undertaken under relevant permits from NMFS and tagging methods were approved by the Institutional Animal Care and Use Committees of PIFSC and CRC. Tags were deployed with a pneumatic projector and were attached to the dorsal fin or just below the fin of the whales by two 6.7 cm titanium darts with backward facing petals. Tags were duty-cycled to only transmit during the hours with the highest probability of a satellite being overhead, with transmissions limited to 10 hours per day. Additionally, the tags were set to transmit every other day after 60 days, and every fifth day after 90 days of deployment.

Photos obtained were used for individual identification and compared to an existing photo-identification catalog to assess population identity (i.e., pelagic or insular) following the protocol outlined in Baird et al. (2008). Dorsal fin photos were also scored for evidence of fisheries interactions as part of the study by Baird et al. (2014). Skin biopsy samples obtained from each group were submitted for genetic analysis to assign each group to a population (i.e., pelagic or insular) using mitochondrial haplotypes, following the procedures outlined in Martien et al. (2014).

Tagged animal locations were determined by the Argos satellite system using Doppler shift of the received signal as the satellite passes overhead. Argos locations have error ellipses ranging in accuracy from a few hundred meters to >10 km (Costa et al., 2010). Each location is assigned a Location Class (LCs) in decreasing order of accuracy: 3, 2, 1, 0, A, B. Each tag includes one GPS position recorded at deployment. Tagged animal locations returned by the Argos system were processed through the Douglas Argos filter (Douglas et al., 2012) with user-defined settings following Baird et al. (2013) to remove unrealistic locations, increasing confidence in the remaining lower quality locations.

To minimize pseudoreplication based on individuals acting in concert, the straight-line distance between all pairs of tagged whale locations was calculated when locations were received within the same satellite overpass. During the period of tag overlap, when the mean distance between a pair of whales was less than 5 km and the maximum distance was less than 25 km, the individuals were considered to be closely associated and acting in concert (Baird et al., 2012). For individuals in close association, the longest duration track was used in the analyses unless otherwise noted.

To characterize pelagic false killer whale spatial use, non-pseudoreplicated positions were compared to areas where longline fishery operations are prohibited, including the Papahānaumokuākea Marine National Monument (PMNM), the longline exclusion zone around the Main Hawaiian Islands (whose boundary was made permanent in 2013 as part of the false killer whale TRP), and the U.S. EEZ around Hawai‘i and Johnston Atoll. The PMNM was expanded in 2016 to include all the waters within the U.S. EEZ around Hawai‘i west of 163°W, and we also assessed locations relative to the expanded boundary. A Kernel-Density Estimation (KDE) analysis was conducted to make an initial estimate of a population range using the

Program R 3.2.5 (R Core Team 2016) package adehabitatHR (Calenge, 2006). Given the small sample size of this dataset, the default bandwidth (h_{ref}) was used, as any concerns about smoothing were secondary to the limited number of individuals used to create the estimate. Areas were determined for 50%, 95%, and 99% of locations, subtracting the area of any islands located within the polygons. Given the small sample size used to generate the range estimate, observer records of interactions from the Hawai‘i-based longline fleets were mapped to illustrate areas where the results are insufficient to produce a representative range for the entire stock.

Logbook data from the Hawai‘i-based longline fisheries was used for all vessels that were fishing during the tag deployment period for a broad area that overlapped with satellite tag data, including both the deep-set and shallow-set fisheries. As logbook data are confidential, any figures, tables or text describing these interactions are necessarily vague regarding location to meet confidentiality requirements. No logbook data or observer records were obtained from any of the longline fleets from other countries operating in the region of concern in this study.

To determine the distance from tagged animal locations, a minimum convex polygon was defined for each longline set, using the positions reported in the logbooks for the beginning and end of the set and the beginning and end of the haul. As the logbook data are dependent on self-reporting of the positions where gear is set and hauled, accuracy of the data were of varying quality, including sets that used the same latitude for all four positions. In cases where set records produced a line instead of a polygon, the beginning of the set point was moved 0.0001° north to change the line into a polygon. The shortest distance from a tagged animal to each longline set polygon was calculated for all tag positions that occurred between the start and end time of the set. The distance of the nearest set (if any) and the ID number of the set was associated with the tag position for analysis of animal response to nearby longlines. Spatial analysis of false killer whale satellite positions in relation to longline sets was conducted using Program R, with distances calculated using the rgeos package (Bivand and Rundel, 2016).

When more than three consecutive positions in an individual false killer whale track were within 100 km of a set, that set was flagged to be analyzed for potential interactions. Time and distance to the set were plotted, as well as the interpolated trackline of the animal in relation to the longline set polygons, allowing for qualitative analysis of whale behavior relative to the set. All flagged sets where animals approached within 50 km were checked to see if an observer was onboard. Groups of false killer whales are often spread out over extended areas, with the largest spread documented by Bradford et al. (2014) of 35 km, making it unlikely that whales associated with a tagged individual would interact with a vessel beyond 50 km. Catch data for sets before, during, and after possible interactions were assessed to determine if there was a reduction in the number of fish caught. For comparisons of whale tracks to longlines, pseudoreplicated tracks were included to increase the ability to detect an interaction. Interactions were only counted once per longline set, no matter how many tagged individuals were involved.

To examine behavior in relation to longline gear, a Switching State-Space Model (SSSM) was used to estimate whale positions at 4-hour time steps and determine the behavior (b) of tagged whales using the BSAM package (Jonsen, 2016; Jonsen et al., 2005) in Program R. B values are a continuous variable with values between 1 and 2. Values <1.25 indicate probable transit behavior, while values >1.75 are considered to be area restricted search (ARS), which is indicative of foraging (Jonsen et al., 2005). Values between 1.25 and 1.75 are treated as undefined. Days when fewer than three whale satellite positions were obtained due to duty cycling were discarded from the analysis. Analyses of differences in b value between the whales tagged in the Northwestern Hawaiian Islands and those tagged off Hawai‘i Island were conducted using a t-test in Program R. Behavior (b) values were examined for all cases when tagged whales had three or more consecutive locations within 100 km of a longline set.

3. Results

Satellite tags were deployed on five pelagic false killer whales in three separate groups, one (PcTagP01) in a group with an estimated 23 individuals on 15 May 2013 in the Northwestern Hawaiian Islands (PIFSC), one (PcTagP02) in a group with an estimated 15 individuals on 26 May 2013 in the Northwestern Hawaiian Islands (PIFSC), and three (PcTag039, PcTag040, PcTag041) in a group with an estimated 16 individuals on 22 October 2013 off Hawaiʻi Island (CRC; Table 1). A total of 28 individuals were photo-identified with good or excellent quality photos in the three different groups, and there were no individuals in common among them. One of the non-tagged individuals encountered on 15 May 2013 had been previously photographed (in September 2010) NE of Midway Atoll during the HICEAS 2010 survey. None of the photographed individuals had dorsal fin injuries that scored high enough to be considered consistent with fisheries interactions (Baird et al., 2014). Four biopsy samples obtained during the 15 May 2013 encounter, one obtained during the 26 May 2013 encounter, and six during the 22 October 2013 encounter were all haplotype 9, the common haplotype documented for pelagic false killer whales (Martien et al., 2014).

After processing with the Douglas Argos filter, there were 2,167 tagged animal locations from the five individuals (Figure 1, Table S1). The two individuals that were tagged in the Northwestern Hawaiian Islands in May 2013 were not associated during the period of tag overlap (mean distance apart = 229 km, SD = 75 km, min = 58 km, max = 355 km), so they were treated separately for analysis purposes. For the three whales tagged in October 2013, the individuals remained closely associated over the period of tag overlap (mean distances apart from 5.4 to 5.7 km, SDs from 3.9 to 4.9 km, min < 1 km, max = 26.4 km); thus, the individual with the longest duration (PcTag041, 123 days) was retained for most analyses.

The two animals tagged in the Northwestern Hawaiian Islands remained within the U.S. EEZ around Hawaiʻi throughout the deployments, using mean depths of 4,147 and 3,702 m, respectively (Figure 1, Table 1). While they spent much of their time offshore, over the abyssal plain, their tracks often intersected with the many islands, atolls and seamounts in this region. Of the 1,228 positions recorded for these two animals, 640 (52.1%) were within the boundaries of PMNM at the time, six were within the longline exclusion zone around the main Hawaiian Islands, and the remaining 582 (47.4%) were outside protected areas and subject to interactions with longline fisheries. With the 2016 expanded PMNM boundary, 1,060 positions (86.3%) would have been within the new boundary. The animal with the longest tag deployment (PcTagP01, 153 days) traveled the length of the Northwestern Hawaiian Islands, from NNE of Kauaʻi in the east, to beyond Midway Island in the west.

The group of animals tagged off Hawaiʻi Island spent some of their time around the seamounts to the south of the island, then headed east, across the abyssal plain, traveling as far as 1,777 km from Hawaiʻi Island. Over the 123-day period they spent 15.3 days (12.5%) inside the U.S. EEZ around Hawaiʻi and 107.4 days (87.5%) in international waters, with a mean depth of 5,208 m (Table 1). At the time of the deployments off Hawaiʻi Island in October 2013, the group was inside the longline exclusion zone around the main Hawaiian Islands. Though the group left the exclusion zone within the first 24 hours post-tagging, they returned to the exclusion zone twice in the first 10 days post-tagging (40 out of 696 positions, 5.7%, for PcTag041 were inside the longline exclusion zone), before spending the remainder of the deployment period outside the longline exclusion zone.

The core range (50th percentile) calculated from the three whale tracks using KDE (h_{ref} = 223,577) was 1,070,289 km^2. The 50% core range is represented by two areas, one to the east of Hawai‘i Island, where PcTag041 spent much of its time, and one broadly covering the central and eastern areas of the Northwestern Hawaiian Islands (Figure 1). The western core area, around the Northwestern Hawaiian Islands, is contained almost entirely within the U.S. EEZ around Hawai‘i, while the eastern core area is mostly outside the EEZ. The 95th percentile spans a range of 4,561,095 km^2, and the 99th percentile covers 6,436,929 km^2, encompassing almost all of the EEZ around Hawai‘i, portions of the EEZ around Johnston Atoll, and high seas areas to the east of the EEZ around Hawai‘i. The longline observer program has recorded 89 false killer whale interactions (i.e., hookings or entanglements) in Hawai‘i-based fisheries between August 1997 and June 2017; of these, 26 (29.2%) were outside the 99% KDE polygon produced for the tagged animals. Only four were in the western core 50% area, and none were in the eastern core area. Of the observed interactions, 38 (42.7%) were within the U.S. EEZ around Hawai‘i, 4 (4.5%) were within the U.S. EEZ around Palmyra Atoll and 47 (52.8%) were in the high seas (Figure 1).

There were 4,190 sets from 461 trips from logbook reports from Hawai‘i-based longline vessels during the period when the tags were deployed, including 4,058 deep sets and 132 shallow sets. Only about 10% of tagged animal positions (n=211) were within 100 km of a longline set, and there were 26 longline sets in which tagged animals were within 100 km for three or more sequential positions. Some sets had tagged individuals approach to within 100 km, while others were set in areas where the animals were already present. The group tagged in

October 2013 had 21 cases with three or more sequential positions within 100 km of a longline set, while the two groups tagged in May 2013 had only a combined five cases that met this criterion. Only two of the three tagged groups (groups with PcTagP01 and PcTag041) came within 50 km of a longline set. No observers were present on any longline vessels where the positions of tagged false killer whales were within 50 km of a set; thus, it was not possible to use observer data to assess interactions.

There were only two cases (each involving three sets, all of deep-set gear) where tagged whales appeared to approach and interact with gear, both involving the group tagged in October 2013. In the first case, the group swam almost 100 km in approximately 7 hours to within a few km of the polygon defined by the set, during gear hauling (Figure 2). The distance from the end of the haul for the first set to the start of the next set was only 16 km (set 1.5 hours later). The group stayed in the area during the second set by the same vessel. The distance from the end of the haul for the second set to the start of the next set was 13 km (2.1 hour later). The tagged whales slowly moved away from the area during the end of the haul on the second set and throughout the third set, returning to the area where they had been prior to approaching the longline vessel. Catches of the target species (bigeye tuna) during the two sets in question (12 and 12) were greater than the catches recorded by the vessel for the three preceding sets (2, 3 and 10) and four subsequent (4, 0, 6 and 5) sets. The three prior sets and four following sets overlapped spatially. Thus, if vessel personnel detected these whales near the gear or found any signs of depredation, the vessel was not moved in response.

The second period of interaction involved tagged individual PcTag041 (tags from the other two individuals in this group were no longer transmitting) following a different deep-set vessel during three sets (Figure 3). The distance between the end of the haul of the first set and the start of the second set, and between the end of the second and start of the third set, was 60 km in both cases (4.5 and 4.83 hours later, respectively). The whale moved closer during the haul for all three sets, suggesting the whale was actively following the vessel. This vessel was one that showed very little drift in positions during some of the sets, suggesting that the recording of the positions were less precise. Combined with inherent uncertainty in Argos-derived locations, it is possible the tagged animals were at the gear (or at least closer to the sets) than results show. Records indicate that the catch of the target species for the first two sets of possible interaction were average (14 bigeye tuna) for the preceding 12 sets on this trip, and the subsequent two sets had an above average catch (25 and 20). On the third set, there was no catch recorded of any species, indicating that depredation may have happened on a large scale during this set. The whale was within 50 km throughout the set, approaching closely during the early phases of the haul. The closest location was within 7 km of the longline polygon, with the subsequent position on the on the opposite side of the polygon, indicating that the whale had crossed through the area of the set. The whale remained within 100 km of the vessel for two more sets, but stayed > 40 km away during the haul.

On four occasions, this same whale was within 50 km of different longline sets (n=4) for more than 3 sequential locations but did not display a noticeable response, passing within 15 km of the nearest longline. In one case, the whale passed 40 km from the end of a set during hauling without approaching. On a different day with another vessel, the whale moved to within 25 km of a set during hauling and then moved away slowly while the haul continued. The next day, the vessel set the longline closer to the individual without an apparent response from the whale, even though it was as close as 11 km at times. The following day, the vessel set its gear near where it fished two days prior, while the whale moved in the opposite direction.

In the one instance where PcTagP01 was within 50 km of a longline the tag was in multi-day duty-cycling and stopped transmitting during the soak stage of the set, so we are unable to assess whether the whale approached the gear during the haul. During the setting of the gear the whale was 9-13 km from where the vessel finished setting the line, and was a greater distance from the gear for most of the process of setting the gear. The catch of the target species on that set was five bigeye tuna, which was slightly above average (mean=3.8) for the 15 sets on that trip, suggesting that large-scale depredation of the catch did not occur.

After filtering for days with fewer than three satellite tag positions, there were 1,071 remaining SSSM locations at a 4-hour time step. Results from the behavior analysis (Table 2) show that the tagged false killer whales spent most of their time in the undefined state between ARS and transit behaviors. Little time was spent in ARS, though it was more common in the Northwestern Hawaiian Islands. Most of the transit behavior was seen in the east end of the range, where the mean behavior value was also much lower than in the Northwestern Hawaiian Islands (Figure 4).This difference in b values between the animals tagged in the Northwestern Hawaiian Islands ($\bar{x}$= 1.50, SD = 0.132) and those tagged off Hawai'i Island ($\bar{x}$= 1.24, SD = 0.105) was significant ($p < 0.001$).

While most ARS periods occurred in the Northwestern Hawaiian Islands, there were four 4-hour periods where the group tagged off Hawai'i Island entered the ARS state. Two of these periods occurred during the two potential interactions and coincided with periods when gear was being hauled (set 1 in Figure 2 and set 2 in Figure 3). The remaining two periods of ARS were consecutive and occurred two days following the second potential interaction. The tagged whale and the vessel were still in the same general area, although the vessel was >50 km from the tagged animal. This case occurred in international waters, so it was possible that there was a foreign vessel fishing in the area.

4. Discussion

This study provides the first assessment of the behavior and movements of pelagic false killer whales across large portions of their range and in relation to longline vessels and fishing gear. We provide corroboration with earlier studies that found that false killer whales respond to the hauling of gear, while providing context to the frequency and distance of the interactions. Our analyses have implications for understanding the interactions between pelagic false killer whales and longline fisheries and thus have relevance to the continuing deliberations of the False Killer Whale Take Reduction Team and their efforts to reduce bycatch in the Hawai‘i-based longline fisheries. The three tagged groups of false killer whales spent varying amounts of time in areas where longline fishing was allowed, but only two of the three groups were ever within 50 km of longline sets. Of those, only one (the group tagged off Hawai‘i Island in October 2013) showed evidence of interacting with longline gear (Figures 2, 3), and only on two occasions (involving a total of just six sets). Recognizing the tagged whale data span relatively short periods (13.6-154.1 days), this limited overlap with known longline sets suggests that not all groups of pelagic false killer whales regularly depredate on longline gear, and even for groups that do, such depredation may represent only a small proportion of their foraging activity. Within the Main Hawaiian Island stock, social groups (or clusters) show varying levels of scarring and mouth line injuries indicative of differing levels of interaction with hook and line fisheries (Baird et al., 2014). There may be similar variability in levels of depredation between and within groups of pelagic false killer whales based on social factors. However, the group that was documented interacting with longline gear spent much of its time in international waters. We have no information on the presence of longline gear set by foreign fleets, and thus it is possible that the whales were regularly interacting with non-U.S. fisheries.

The details of the longline interactions documented provide some insights into the nature of the interactions. In both cases, the tagged whales remained in the area for a series of multiple gear sets by the same vessel. Initial approaches of whales towards the vessels appear to occur during the hauling of the gear, supporting the hypothesis that the whales are attracted to acoustic signals during the haul (Bayless et al., 2017), though the whales remained in the area during subsequent sets, which would support the contention of the captains that depredation can occur during all phases of fishing (TEC Inc., 2009). The change of behavior state to ARS during these potential periods of interaction offers additional support that the whales are responding specifically to the hauling of the gear, though it remains a possibility that the whales and the longline vessels are targeting the same concentration of fish. Of the six longline sets during the two interactions, only one set had a reduction in catch that suggested wholesale depredation, with catches on other sets in the series having a similar or greater number of fish caught compared to the earlier or later sets during the trip. It is possible that any depredation may have been concentrated on the bait, rather than the catch, but this finding also brings up the possibility that while pelagic false killer whales might respond to the vessels, they may not depend on depredation of the bait or catch if there is sufficient food available in the general area. Logbooks recorded several above-average catch rates during these interactions which could signify plentiful prey in the area. Interviews with Hawai‘i-based captains have noted their belief that both whales and longlines will concentrate in areas where the fish are located, increasing the probability of interactions (TEC Inc., 2009). The longline vessel in the first interaction provides an example of vessels continuing to fish in the same location for all three sets while false killer whales were in the area, instead of moving, which is a common response to finding evidence of depredation (TEC Inc., 2009).

Many sets within 50 km were bypassed by the tagged whales without a noticeable response to the nearby vessels or fishing gear. Overall, tagged animals ignored nearby longlines more often than they responded to them, occasionally ignoring multiple nearby longline sets. Such results suggest that, at least for the groups containing the tagged animals, the preferred method of obtaining food is not necessarily depredation, though it may occur at times, agreeing with the findings in Bayless et al. (2017). Given the length of these longlines, questionable record keeping in the case of some sets, the accuracy of Argos-derived positions (Table S1; Costa et al., 2010), and the expansive area that can be covered by members of a single false killer whale group (Baird et al., 2008; Bradford et al., 2014), it is possible that some whales which appear to be several km away could actually be closer to (or farther from) the longline than the distance would suggest.

Our tagging results also have implications for the range of the Hawai‘i pelagic false killer whale population in relation to both U.S. and foreign longline fisheries. It is clear that pelagic false killer whales have a range that extends far offshore of the Hawaiian Islands and broadly overlaps with international waters. The locations of the tagged animals and interactions with longline vessels reported by observers suggest that their range extends at least from 179°W to 137°W longitude, and from 5°N to 31°N latitude. Biases are introduced to these samples by the nature of how they were collected. Tag deployment locations are near the islands and within the U.S. EEZ around Hawai‘i, and the observer locations and fisheries interactions are dictated by the regions fished by the Hawai'i-based longline fleet. The KDE provided a useful estimate of the range from east to west, but is limited by the small number of tags deployed, which are insufficient to reveal the full extent of the range of the population, missing areas where observers have documented pelagic false killer whale presence. Even with these limitations, it is notable that the two core areas for the tagged animals that were identified by the KDE are near areas that vessel captains identified as depredation hotspots (TEC Inc., 2009).

As a transboundary stock, with most of its range outside the U.S. EEZ around the Hawaiian Islands, it is difficult to properly assess and monitor the impact of the combined fisheries of many nations on the pelagic false killer whale population. NMFS monitors and calculates abundance estimates for the portion of the stock that is found within the U.S. territorial waters (Bradford et al., 2014; Carretta et al., 2017), but has not assessed the entire stock, as there has been only limited survey effort in areas outside the U.S. EEZ. In terms of foreign fisheries, annual reports to the WCPFC demonstrate varying levels of observer coverage and reporting of marine mammal bycatch among the member countries, also making it challenging to monitor fisheries-related takes of false killer whales on the high seas. To improve the monitoring of this stock throughout its range, additional efforts are needed to collect and evaluate data from these foreign fisheries, as well as to tag and conduct surveys in international waters.

Little is known about this population of pelagic false killer whales, as their low-density and distribution in offshore waters makes them difficult to study, opening many areas for future study, none of which are easy. Continuing efforts are needed throughout their range to photograph and tag individuals to better understand their movements and social structure, and how that relates to interactions with the longline fishery. Tag deployments should be spread across both years and regions, with a concentration on those groups thought to enter areas with longline activity to increase the probability of detecting fisheries interactions. Efforts should also be made to expand this work to include fishing data from other nations that fish in areas overlapping with this population of whales, using the larger datasets to not only study the interactions of false killer whales and longlines, but also determine what environmental factors are driving decisions of the whales in relation to the fisheries. As it appears that whales often ignore nearby vessels, acoustic analyses should be conducted to determine if there is a difference in acoustic signatures of vessels that do or do not experience depredation. It is likely that individuals in the pelagic population live in discrete social clusters, similar to those in the Main Hawaiian Islands population (Baird et al. 2012; Martien et al. 2019). Increasing the number of images of individuals, through collaboration with fishermen and the observer program as well as through directed efforts, would make it possible to determine if these social clusters exist, document their members, and assess how ranges and interactions with fisheries may vary by social group.

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DATA AVAILABILITY STATEMENT

Longline fishery logbook data is restricted due to confidentiality requirements, and is available only through non-disclosure agreement with NMFS. CRC false killer whale location data is available from RWB upon reasonable request. PIFSC false killer whale location data is available from EMO upon reasonable request.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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Tables

Table 1: Details on satellite tag deployments on pelagic false killer whales, after filtering through the Douglas Argos filter. Whales PcTag039 and PcTag040 were found to act in close association with PcTag041, so they were excluded from most analyses.

Tag ID	Deploy Date	End Date	# days	# positions	Cumulative distance moved (km)	Distance (km) from tagged animal location (mean/SD)	Distance (km) from shore (mean/SD)	Depth (m) (mean/SD)	#/% inside longline exclusion areas
PcTagP01	2013-05-15	2013-10-16	154.1	1,075	12,857	529.4/328.4	135.3/74.3	4,174/1,109	558/52%
PcTagP02	2013-05-26	2013-06-09	13.6	153	1854	187.7/81.9	243.1/57.1	3,702/1,127	82/54
PcTag039	2013-10-22	2013-11-03	11.8	103	1,409	147.2/58.3	101.9/49.9	4,475/764	36/35%
PcTag040	2013-10-22	2013-11-07	15.8	140	1,878	210.9/145.2	146.8/112.5	4,686/679	39/28%
PcTag041	2013-10-22	2014-02-22	122.7	696	12,735	798.5/470.8	693.1/454.1	5,208/515	40/5.7%

Table 2: Behavior (b) results for the 4-hour time step Switching State-Space Model (SSSM). Values of $b < 1.25$ are considered transit, while $b > 1.75$ are considered area restricted search (ARS). NWHI = Northwestern Hawaiian Islands.

Region tagged	SMMM locations	b Mean/SD	#/% Transit	#/% ARS
All	1,071	1.39/0.17	295/27.6%	14/1.3%
NWHI	608	1.50/0.11	8/1.3%	10/1.6%
East	463	1.24/0.13	288/62.2%	4/0.86%

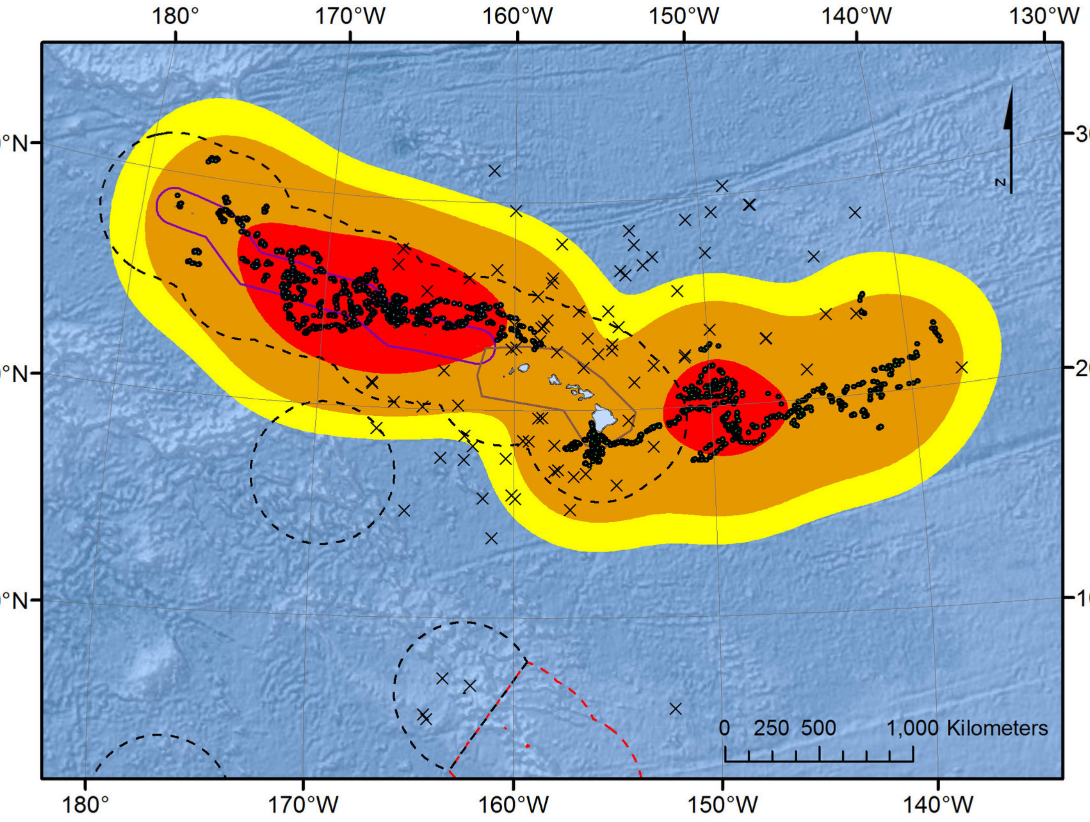
Figures

Figure 1: Kernel Density Estimation of range for three groups of false killer whales tagged in 2013. Area in red, orange, and yellow represent areas with 50%, 95%, and 99% of tag locations (black circles), respectively. Black × symbols represent locations where fisheries observers have recorded interactions. The black dashed outlines are the U.S. Exclusive Economic Zone (EEZ) around Hawaiʻi, Johnston Atoll, Palmyra, and Howland Island. The dashed red line is the Kiribati EEZ. Areas where longline fisheries were prohibited as of 2013 have solid outlines in purple (Papahānaumokuākea Marine National Monument) and brown (longline exclusion zone).

Figure 2: Interaction of three false killer whales (tagged off Hawaiʻi Island) with a series of three consecutive deep-set longline sets. During the first longline set, a rapid approach from almost 100 km occurred during hauling of the gear. The three individuals remained close to the gear through most of the second set, before slowly moving away during hauling and into the next set. The three individuals are denoted by shape (circles, squares, diamonds). Longlines and their corresponding time periods are denoted by color: green (first set), brown (second set), yellow (third set). a) Distances of individuals to longlines are represented during the three sets. b) Spatial overlap between individuals and longline fishing gear.

Figure 3: Interaction of a false killer whale (tagged off Hawaiʻi Island) with a series of three deep-set longline sets. a) This individual appears to be following the vessel, approaching during hauling. b) Spatial overlap during the three sets. See Figure 2 caption for explanation of symbols/colors. The white circles represent whale locations during periods in between sets.

Figure 4: Box plot showing the difference in behavior states, generated through the use of a Switching State-Space Model with a 4-hour time step, between the whales tagged in the Northwestern Hawaiian Islands and those to the east of Hawai‘i Island. The middle lines represent the median value, with the upper and lower lines of the box representing the 1st and 3rd quartiles. The vertical lines represent values within 1.5 times the inter-quartile range, while the points above or below the lines represent the remaining values. High behavior values (>1.75) represent time spent in area restricted search, which is commonly associated with foraging. Lower values (<1.25) represent transit behavior, with little time spent foraging.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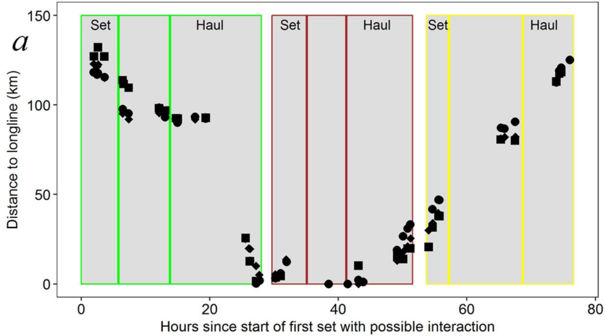
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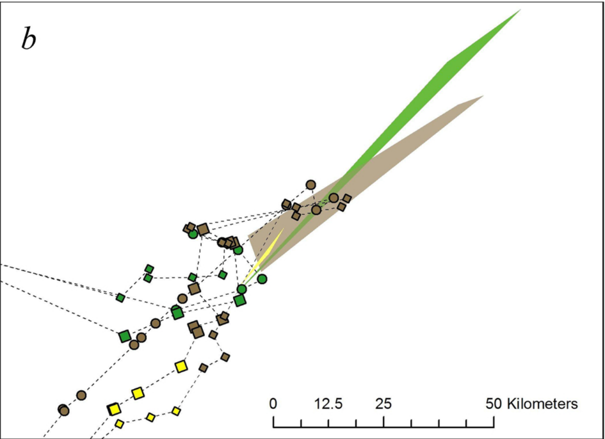
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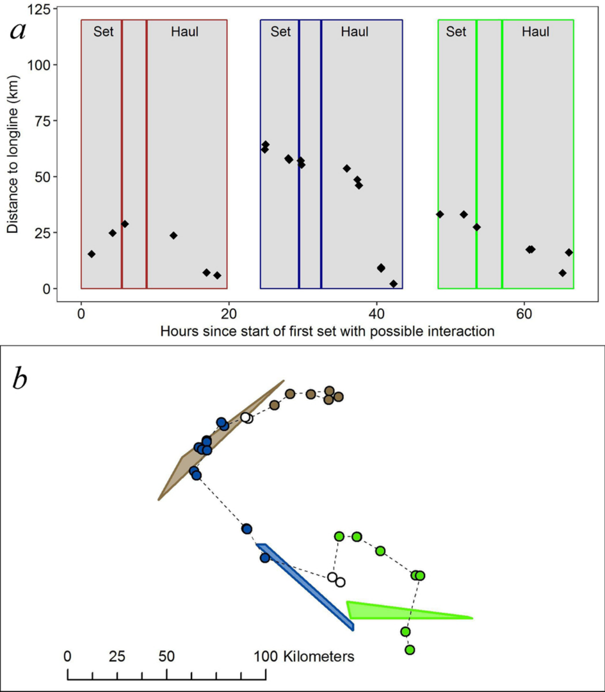
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Hours since start of first set with possible interaction
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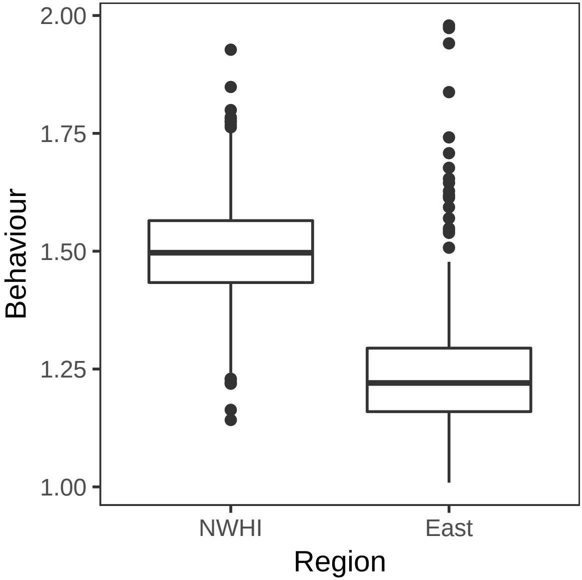
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