MOVEMENTS AND SPATIAL USE OF FALSE KILLER WHALES IN HAWAI‘I: SATELLITE TAGGING STUDIES IN 2009

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Summary

Movements and spatial use of Hawaiian insular false killer whales was examined using data from nine individuals satellite-tagged in 2009; five tagged off the island of Oʻahu in October and four tagged off the island of Hawaiʻi in December. A total of 3,782 locations were available after filtering, over periods up to 104.8 days (median = 70.7 days), more than doubling the location data available from this population. Assessment of distance between pairs of individuals with overlapping data indicated we obtained movement information from at least five and possibly seven different social groups of false killer whales. All tagged individuals remained in association with the main Hawaiian Islands. While movements of one individual extended up to 112.8 km from shore, into a water depth of approximately 5,400 m, the average distance from shore ranged from about 11 to 23 km, in depths averaging about 500 to about 1,200 m. Four of the five individuals tagged off Oʻahu moved west to Kauaʻi and Niʻihau, providing evidence the Hawaiian insular population uses the waters around the westernmost of the main Hawaiian Islands. There were no significant differences in the proportion of time spent using windward versus leeward sides of the islands. One individual that had been tagged previously (in 2008) showed very different spatial use patterns in 2008 versus 2009. Overall the data provides a more robust assessment of spatial use and movements of Hawaiian insular false killer whales that can be used in helping assess critical habitat if this population is listed under the Endangered Species Act.

Introduction

Two stocks of false killer whales have been recognized in Hawaiian waters, an open-ocean (“pelagic”) stock, and an insular stock found around the main Hawaiian Islands (Chivers et al. 2007, 2010; Baird et al. 2008; Carretta et al. 2010; Oleson et al. 2010). In recent years, confirmation of the small population size, evidence of a decline in abundance, and a variety of threats have led to a proposal to list the Hawaiian insular population as Endangered under the U.S. Endangered Species Act (ESA) [Reeves et al. 2009; Baird 2009; Oleson et al. 2010; Federal Register 2010]. If the Hawaiian insular population is listed, it would be only the fourth listing of a cetacean under the ESA since 1973, and such a listing would require preparation of a recovery plan and designation of critical habitat.

Information on habitat use and movements of Hawaiian insular false killer whales comes from two primary sources, boat-based surveys utilizing photo-identification of distinctive individuals (e.g., Baird et al. 2008), and locations obtained from individuals tagged with remotely-deployed satellite tags (Baird et al. 2010a). Given the low population density and the difficulty and expense of surveying in windward and offshore waters, information from satellite tagging provides a much more detailed and less biased representation of habitat use and movements than can be obtained from boat-based surveys. Prior to 2009 satellite tags had been deployed on one individual from the pelagic stock and three groups (11 individuals) from the insular stock (Baird et al. 2010a). The tags deployed on insular stock false killer whales have provided information on the: 1) extent and rates of movements among the main Hawaiian Islands; 2) offshore extent of movements of tagged whales; 3) their use of the windward sides of the islands; and 4) coordination of movements of individuals within groups (Baird et al. 2010a).

Despite the substantial increase in knowledge over what was known from boat-based studies (Baird et al. 2008), there are serious limitations to the existing data set in terms of inferences that can be made about movements of the population as a whole. Prior to 2009 all the tags had been deployed on individuals off the island of Hawai‘i, and movements appear to be somewhat influenced by where individuals are when they are tagged (Baird et al. 2010a). Although 11 individuals from the insular population were tagged, tags were deployed in only three different groups of false killer whales (based on proximity when tags were deployed), and movements of individuals within groups is not independent. Movements may also be influenced by variable eddy fields (e.g., Seki et al. 2001, 2002), as well as seasonal and inter-annual variation in prey abundance and movements (Oleson et al. 2010). There is also likely variation in movement and habitat use patterns depending on whether individuals have prior experience with depredation from fishing gear (Chilvers and Corkeron 2001; Powell and Wells 2011). False killer whales around the main Hawaiian Islands do depredate catch from fishing vessels (Shallenberger 1981) but it is unknown whether some or all individuals in the population depredate catch. Lastly, given the strong social bonds among individual false killer whales (Baird et al. 2008), there may be variation in movement patterns among groups within the insular population, similar to variations in movements among pods within populations of fish-eating ("resident") killer whales (e.g., Hauser et al. 2007). Tags deployed may not effectively represent all the distinct social groupings within the insular population of false killer whales.

To address some of these limitations, additional efforts to deploy satellite tags on individual false killer whales were made in 2009, with field efforts off the island of Hawai‘i and off the island of O‘ahu. This report summarizes results from tag deployments on false killer whales in 2009.

Methods

Methods used followed Baird et al. (2010a). The tags used were based on a design of Andrews et al. (2008), which have been used on 16 species of cetaceans (e.g., Schorr et al. 2009a, 2009b; Baird et al. 2010b, 2011). The tag contained a Wildlife Computers (Redmond, Washington, USA) ARGOS-linked SPOT-5 location-only Platform Transmitter Terminal in the Low Impact Minimally Percutaneous External-electronics (LIMPET) configuration. The Limpet tag attaches with two 6.5 cm penetrating titanium darts with backward facing petals. Dimensions of the tag (without darts) were 63 x 30 x 21 mm, and the total weight of the entire tag package was approximately 49 g. Tags were duty cycled in one of two ways. One tag (originally intended for deployment on a killer whale) transmitted for 50 days, 10 hours per day in five two-hour blocks spread throughout the day corresponding to the greatest density of satellite passes. After day 50 the tag transmitted every 2nd day for 12 days, then every 3rd day. The other tags transmitted daily for 60 days, nine hours per day during five blocks ranging from 1-3 hours in duration, after which they transmitted every 2nd day until day 90, and then every 5th day afterwards. To reduce battery draw and thus increase the period over which tags would transmit, the minimum interval between transmissions was increased from 30 seconds (used in the 2007 and 2008 deployments) to 45 seconds. Tags were remotely-deployed on false killer whales using a Dan-Inject JM Special 25 (Børkop, Denmark) pneumatic projector.

Photographs of tagged and companion individuals were compared to an existing photo-identification catalog that includes individuals from both the insular population and the offshore population, following the protocols described by Baird et al. (2008). Age class (adult, sub-adult) of tagged individuals was estimated based on body size relative to other individuals, both in the field and in photographs, as well as by sighting history for some individuals. Each individual was designated by an alphanumeric catalog number (HIPc###) after Baird et al. (2008).

Satellite-derived locations were assessed for plausibility using the Douglas Argos-Filter, Ver. 7.08 (available at http://alaska.usgs.gov/science/biology/spatial/douglas.html), using two independent methods (distance between consecutive locations, and rate and bearings among consecutive movement vectors). A number of variables are user-defined: location classes (LCs) that are automatically retained; maximum sustainable rate of movement; maximum-redundant-distance (consecutive points within a defined distance are kept by the filter); and the rate coefficient (Ratecoef) for assessing the angle created by 3 consecutive points. The rate coefficient algorithm takes into account that the further an animal moves between locations, the less likely it is to return to or near to the original location without any intervening positions, creating an acute angle characteristic of typical Argos error. We automatically retained LC2 and LC3 locations, with estimated error of < 500 m and < 250 m, respectively (Argos User's Manual). LC1 locations (with estimated error of between 500 and 1 500 m), as well as LC0, LCA, LCB, and LCZ locations (with no estimation of accuracy) were only retained if they passed the Douglas Argos-Filter process. For maximum sustainable rate of movement, we used 20 km h^{-1}, based on maximum travel speeds noted during observations of fast traveling false killer whales in Hawai‘i (Baird, pers. obs.). Maximum redundant distance was set at 3 km, and Ratecoef was set at 25.

For all filtered locations, a number of variables were populated using ArcGIS v. 9.2 (ESRI, Redlands, California), with point location data layered on a bathymetric raster surface. These included depth, distance to shore, and distance to the longline fishery boundaries, as well as whether locations were on the windward (north and east) or leeward (west) sides of the islands, following the methods of Baird et al. (2010a). For one individual that had been previously tagged in 2008 (reported in Baird et al. 2010a), data from the previous tag deployment were compared to assess variability in movement patterns.

Given the evidence of strong social relationships from photo-identification data (Baird et al. 2008), we assessed whether tagged individuals might be part of the same social groups. The straight-line distance (i.e., not taking into account potentially intervening land masses) between pairs of individuals was calculated when locations were obtained during a single satellite overpass. Average distances between pairs of individuals were calculated and distance between individuals over time was graphically represented.

Results

In the fall of 2009, 11 satellite tags were deployed on false killer whales around the main Hawaiian Islands on seven days during two separate field efforts (Table 1). Five of these were deployed on five different days off the island of O‘ahu (over a 12-day span in October 2009), and the remaining six were deployed on two days off Hawai‘i in December 2009. One of the tags deployed in December 2009 was on an individual with evidence of a previous interaction with line fisheries (HIPc186, shown in Baird and Gorgone 2005), but no transmissions were received from this tag. One other tag deployed in December 2009 also appeared to fail on impact, thus data were received from nine tags (deployed on seven days). All individuals were photo-identified and were either previously documented individuals from the Hawai‘i insular population (six individuals), or other individuals in the group were matched to the Hawai‘i insular population. Of the nine individuals, seven were considered distinctive or very distinctive, and two were considered slightly distinctive or not distinctive (cf. Baird et al. 2008). One of the individuals tagged (HIPc145) had been previously tagged in July 2008.

After filtering, a total of 3,782 locations were obtained, with data received over periods from 11 to 104.8 days (median = 70.7 days). Approximately 68% of all locations after filtering were location classes 3, 2 or 1 (Table 2).

All tagged individuals remained around the main Hawaiian Islands (Figure 2, Figure 5). Four of the five individuals tagged off Oʻahu moved west to Kauaʻi and Niʻihau (Figure 2, Figure 5), and three of the five moved east to the island of Hawaiʻi. The one individual tagged off Oʻahu that was not documented moving to the island of Hawaiʻi (HIPc314) had been previously documented off Hawaiʻi Island in 2008 and was subsequently documented off Hawaiʻi Island in 2010.

Patterns of distance from shore over the time since tagging varied considerably among individuals, with some individuals repeatedly moving to distances of 50 or more kilometers from shore and others remaining relatively close to shore (e.g., <40 km) for the duration of tag transmission (Figure 3, Figure 4). The furthest from shore documented for one individual was 112.8 km (Table 4). Median distance from shore varied from approximately 10 kilometers to 23 kilometers, and median water depth varied from about 500 m to over 1,200 m (Table 4; Figure 6).

Movement data for HIPc145 were available in 2009 (n=416 locations over 61 days) and 2008 (n= 202 locations over 20 days). HIPc145's distance from shore was significantly greater in 2009 (median = 11.5 km) than in 2008 (median = 6.4 km; Mann-Whitney U-test, $p < 0.0001$), although average depth did not differ significantly (2009 median = 497 m, 2008 median = 391 m; Mann-Whitney U-test $p = 0.0669$). In 2008 HIPc145 remained only around the island of Hawaiʻi, whereas in 2009 HIPc145 moved throughout the main Hawaiian Islands (Figure 5).

Assessing whether individuals with temporally overlapping tag data were part of the same social group was undertaken both within tagging periods (October or December), and between the two tagging periods, as three of the five individuals tagged in October still had transmitting tags when the additional four individuals were tagged in December, resulting in a total of 28 pair combinations (Table 3). Although the closest distance between two individuals was often less than 1 km (e.g., HIPc314 had locations <1 km from four of the other eight individuals; Table 3), average distances among individuals indicated in most cases that individuals were not consistently close (e.g., mean distance of HIPc314 to the other eight individuals ranged from 68.7 km to 223.8 km; Table 3). Based on average distances among pairs of tagged whales over time, two pairs of tagged whales (HIPc357 and HIPc358, tagged one day apart off Oʻahu; and HIPc145, tagged off Oʻahu in October and HIPc115, tagged off Hawaiʻi Island in December) remained relatively close (<20 km) during the periods of tag overlap (Table 3; Figure 1). Three other pairs (HIPc358 with each of HIPc347 and HIPc365, and HIPc347 and HIPc365) had relatively small average distances (30.4 km, 12.4 km, and 18.8 km, respectively, Table 3), but also moved considerable distances apart (>160 km, >60 km, >140 km, respectively; Figure 1).

Assessment of use of windward versus leeward sides of the islands was undertaken both for all individuals (Table 4), and excluding data from HIPc357 and the overlapping data from HIPc115, given the likelihood that these pairs are part of the same social grouping. There was no significant difference in the proportion of time spent on windward or leeward sides of the islands for either the entire sample (median windward 42.6%, leeward 57.4%; Mann-Whitney U-test p = 0.2893) or the reduced sample (median windward 47.9%, leeward 52.0%; Mann-Whitney U-test p = 0.8748).

Discussion

Efforts to satellite tag Hawaiian insular false killer whales in 2009 more than doubled the number of groups that had been tagged and the total number of satellite-derived locations from this population. With changes to the duty cycling of the tags and continued improvements in tag design, location data were obtained over a considerably longer span of time (median = 70.7 days) than for those tags deployed on false killer whales in 2007 and 2008 (median = 30.2 days; Baird et al. 2010a). Although location qualities were good (68% of filtered locations of LC3, LC2 or LC1), there was a reduction in the proportion of LC3, LC2 and LC1 class locations over tags deployed in 2007 and 2008 (75%; Baird et al. 2010a). Such a tradeoff seems warranted given the increased timespan over which locations were obtained in 2009.

In general, all tagged individuals remained in association with the main Hawaiian Islands (Figure 7), further supporting that this population is resident to the main Hawaiian Islands. The proportion of time individuals spent on the windward or leeward sides of the islands varied considerably, ranging from approximately 21% to 78% of locations documented on the windward sides of the islands (Table 4), although overall there was no significant difference in the time spent on the windward or leeward sides of the islands.

Prior to this effort all the satellite data available were from individuals tagged off the island of Hawaiʻi (Baird et al. 2010a). During this effort five individuals were satellite tagged off the island of Oʻahu on five different days over a 10-day span, allowing for a comparison of movements of individuals tagged off Oʻahu versus those tagged off Hawaiʻi Island. Two of these individuals were in close proximity (<20 km) for the 10 days during which data were received for both tags (Figure 1). However, despite the fact that some of the other individuals came into close proximity during the periods their tags were functioning, these periods were relatively short in duration (e.g., a few hours, e.g., Figure 1), thus it appears as if data were effectively obtained from four different groups. The four groups did vary considerably in terms of depths used (median ranging from 497 m to 1229 m), distance from shore (median ranging from 10.2 km to 23.2 km), and tendency towards the western versus eastern main Hawaiian Islands (Figure 2). In comparison to false killer whales tagged off Hawaiʻi Island both in 2007/2008 and in 2009, the whales tagged off Oʻahu spent more time further west in the main Hawaiian Islands, with three of the four groups spending time around Niʻihau and Kauaʻi (Figure 2, Figure 7), indicating that there is some effect of tagging location on the movement patterns of individuals. This suggests that future tagging efforts should be spread throughout the range of this population, to capture such variability.

Assessing whether individual false killer whales with overlapping tag data are part of the same social group is problematic, given the typical widely dispersed nature of groups encountered in the field (Baird et al. 2008), and the tendency of individuals to split and re-join based on satellite data (Baird et al. 2010a). Using average distances among pairs of locations of individuals and the patterning of splitting and re-joining we believe we tagged four different social groups off O‘ahu (Figure 1, Table 3), but at least one of the individuals tagged off O‘ahu is likely from the same social group as one tagged off Hawai‘i Island. Most of the pair combinations (23 of 28) of whales with overlapping data had average distances between them of from approximately 57 km to 249 km (Table 3), and it seems obvious that such pairs are not members of the same social group, despite the fact that many of them do occasionally come into close proximity (Table 3). Three other pairs of whales had average distances among locations ranging from 12.4 to 30.4 km, and all three pairs spent periods of five or more days in close (<10 km) proximity (Figure 3), yet also separated widely (>60 to >160 km). Whether these whales may be from the same social group is unclear based on our data. Thus, of the nine individuals that we have movement data on from tagging in 2009, we have data from at least five social groups and possibly as many as seven social groups.

In comparison to data from tagged whales in 2007 and 2008 (Baird et al. 2010a), individuals were documented further offshore on both the leeward and windward sides of the islands (Figure 7), and were documented using the southeast coast of the island of Hawai‘i (Figure 7), suggesting that as sample size increases more variability in movement patterns will continue to be documented. Although no individuals were documented crossing the longline exclusion boundary (Figure 7), individuals approached relatively close to this boundary on both the windward and leeward sides of the islands.

The population of Hawaiian insular false killer whales is currently being considered for listing under the Endangered Species Act (Federal Register 2010), and if listed, NMFS may designate critical habitat. This data set, particularly when combined with location data obtained from satellite-tagged individuals in 2007 and 2008 (Baird et al. 2010a), and seven additional individuals tagged in 2010 (Baird et al. unpublished data), will allow for a relatively unbiased assessment of the range of the population as well as determination of which areas are used the most. In additional to location information, dive data were obtained from three of the tags deployed in 2010 (see e.g., Baird et al. 2010b), which will allow for future analyses of behavior in relation to habitat and may allow for an assessment of which areas are particularly important for foraging.

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Table 1. Information on false killer whales tagged[1] during 2009

Temp Animal ID	ID	Island tagged off	Date tagged	Date last location	# days transmit	# days locations	Age class
PcTag13	HIPc314	O‘ahu	5-Oct-09	2-Jan-10	88.9	75	Sub-adult
PcTag14	HIPc357	O‘ahu	13-Oct-09	24-Oct-09	11.0	12	Adult
PcTag15	HIPc358	O‘ahu	14-Oct-09	16-Jan-10	93.9	76	Adult
PcTag16	HIPc317	O‘ahu	16-Oct-09	16-Nov-09	31.0	31	Adult
PcTag17	HIPc145	O‘ahu	17-Oct-09	27-Dec-09	70.7	61	Adult
PcTag20	HIPc347	Hawai‘i	10-Dec-09	19-Mar-10	98.9	76	Adult
PcTag21	HIPc365	Hawai‘i	10-Dec-09	26-Dec-09	16.1	16	Adult
PcTag22	HIPc351	Hawai‘i	18-Dec-09	2-Apr-10	104.8	77	Sub-adult
PcTag23	HIPc115	Hawai‘i	18-Dec-09	28-Jan-10	40.7	41	Adult
Median					70.7	61	

[1]Individuals with functioning tags only.

Table 2. Percentage of all locations for each individual that passed the Douglas Argos-Filter, by location class (LC)

ID	# locations after filtering	LC3	LC2	LC1	LC0	LCA	LCB	LCZ
HIPc314	610	7.54	24.59	35.57	20.66	5.57	5.57	0.49
HIPc357	106	6.60	27.36	44.34	10.38	7.55	2.83	0.94
HIPc358	660	5.30	33.48	38.33	11.67	5.15	6.06	0.0
HIPc317	266	9.02	29.32	33.08	14.29	7.52	6.77	0.0
HIPc145	416	9.13	29.81	32.69	14.42	6.97	6.73	0.24
HIPc347	673	6.84	25.26	40.86	12.63	8.32	5.94	0.15
HIPc365	132	4.55	22.73	27.27	12.88	18.18	14.39	0.0
HIPc351	581	8.43	21.69	27.71	11.88	15.66	14.63	0.0
HIPc115	338	8.28	26.92	26.92	10.06	15.38	12.43	0.0
Mean		7.30	26.80	34.09	13.21	10.03	8.37	0.20

Table 3. Distance (km) among all possible pairs of locations obtained during the same satellite overpass of individual false killer whales tagged in 2009. Cells above the diagonal are the distances of the closest pair of locations. Cells below the diagonal are the mean distance of all pairs of locations. Cells designated N/A are for pairs of whales that did not overlap temporally. Cells in bold are individuals that may be from the same social group based on proximity (see also Figure 1)

ID	HIPc314	HIPc357	HIPc358	HIPc317	HIPc145	HIPc347	HIPc365	HIPc351	HIPc115
HIPc314	-	1.8	0.6	0.5	0.2	0.3	8.7	18.7	37.2
HIPc357	152.2	-	0.4	99.4	0.5	N/A	N/A	N/A	N/A
HIPc358	101.5	**3.4**	-	98.2	0.5	0.2	0.2	1.2	33.6
HIPc317	223.8	249.2	219.6	-	0.5	N/A	N/A	N/A	N/A
HIPc145	68.7	124.9	93.8	204.5	-	41.1	39.7	5.5	0.2
HIPc347	115.5	N/A	**30.4**	N/A	138.9	-	0.4	0.2	16.1
HIPc365	137.1	N/A	**12.4**	N/A	148.0	**18.8**	-	0.4	75.8
HIPc351	96.0	N/A	66.3	N/A	110.5	56.7	57.3	-	4.6
HIPc115	181.0	N/A	151.7	N/A	**2.9**	170.4	149.7	169.8	-

Table 4. Characteristics of location data from false killer whales satellite-tagged in 2009

ID	Max distance (km) from deployment	Distance to shore (km) Median (range)	Water depth (m) Median (range)	% windward	% leeward
HIPc314	274	10.2 (0.03-66.3)	501 (3-4,464)	42.55	57.45
HIPc357	208	15.8 (0.20-56.9)	1085 (1-3,780	22.43	77.57
HIPc358	390	23.2 (0.4-112.8)	1229 (8-5,401)	21.33	78.67
HIPc317	317	17.6 (0.3-67.3)	825 (4-4,489)	63.67	36.33
HIPc145	314	11.5 (0.1-79.2)	497 (3-4,854)	28.37	71.63
HIPc347	287	17.3 (1.8-66.8)	687 (51-4,787)	78.04	21.96
HIPc365	224	23.5 (4.0-79.7)	1165 (48-4,802)	21.05	78.95
HIPc351	276	14.4 (0.5-39.9)	652 (14-3,789)	53.44	46.56
HIPc115	176	10.9 (0.05-38.9)	603 (9-2,465)	75.29	24.71
Grand mean		16.0	805	45.13	54.87

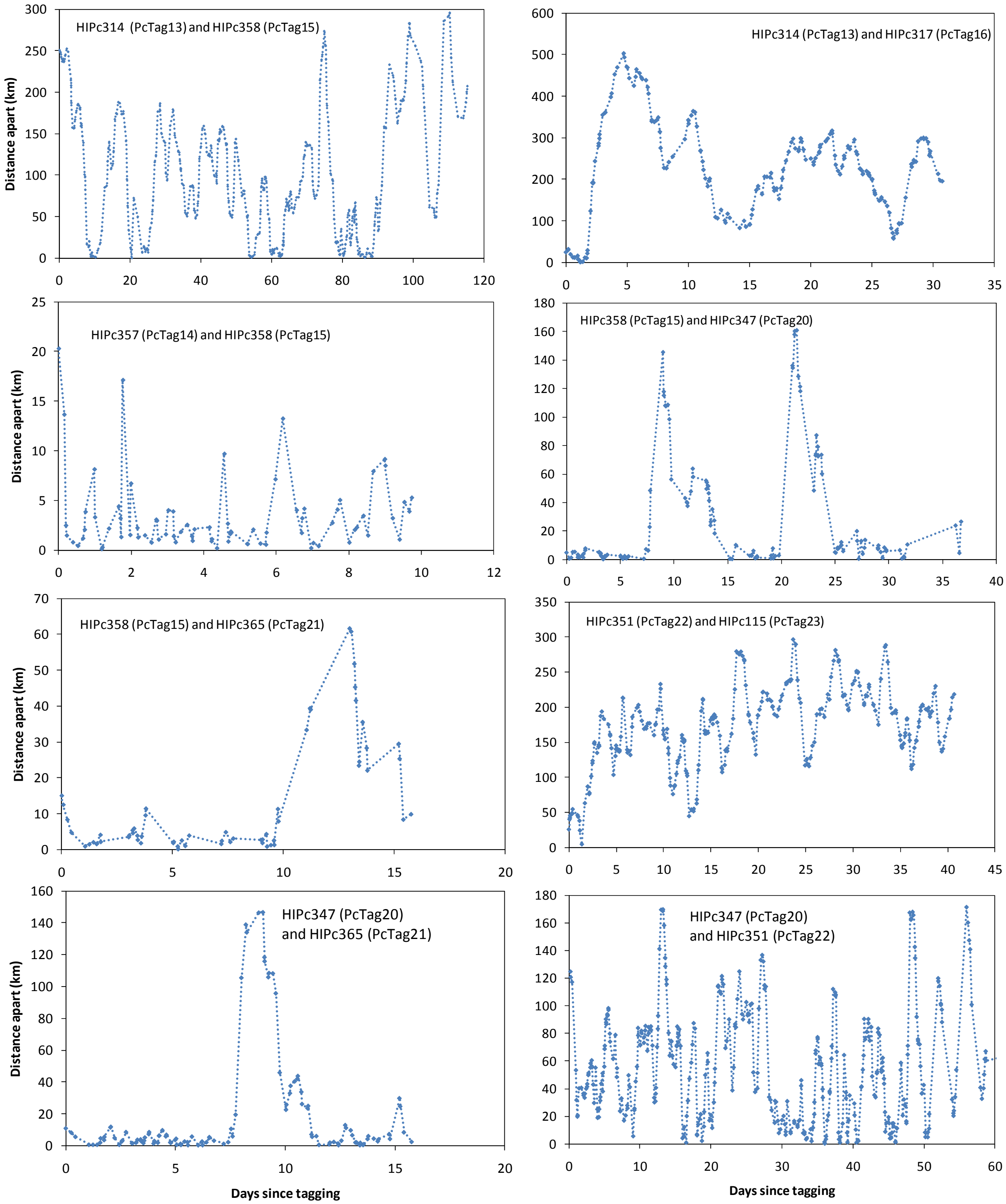

Figure 1. Examples of distance among pairs of individual false killer whales during single satellite overpasses. The X-axis scale begins when the second whale in the pair was tagged except when both whales tagged on the same day (HIPc351 and HIPc115). Note varying X- and Y-axis scales. Of all the potential pairs of whales, only two pairs (HIPc357 and HIPc358, row 2, left column; and HIPc145 and HIPc115, not shown) remained relatively close (<20 km) over the duration of overlapping data.

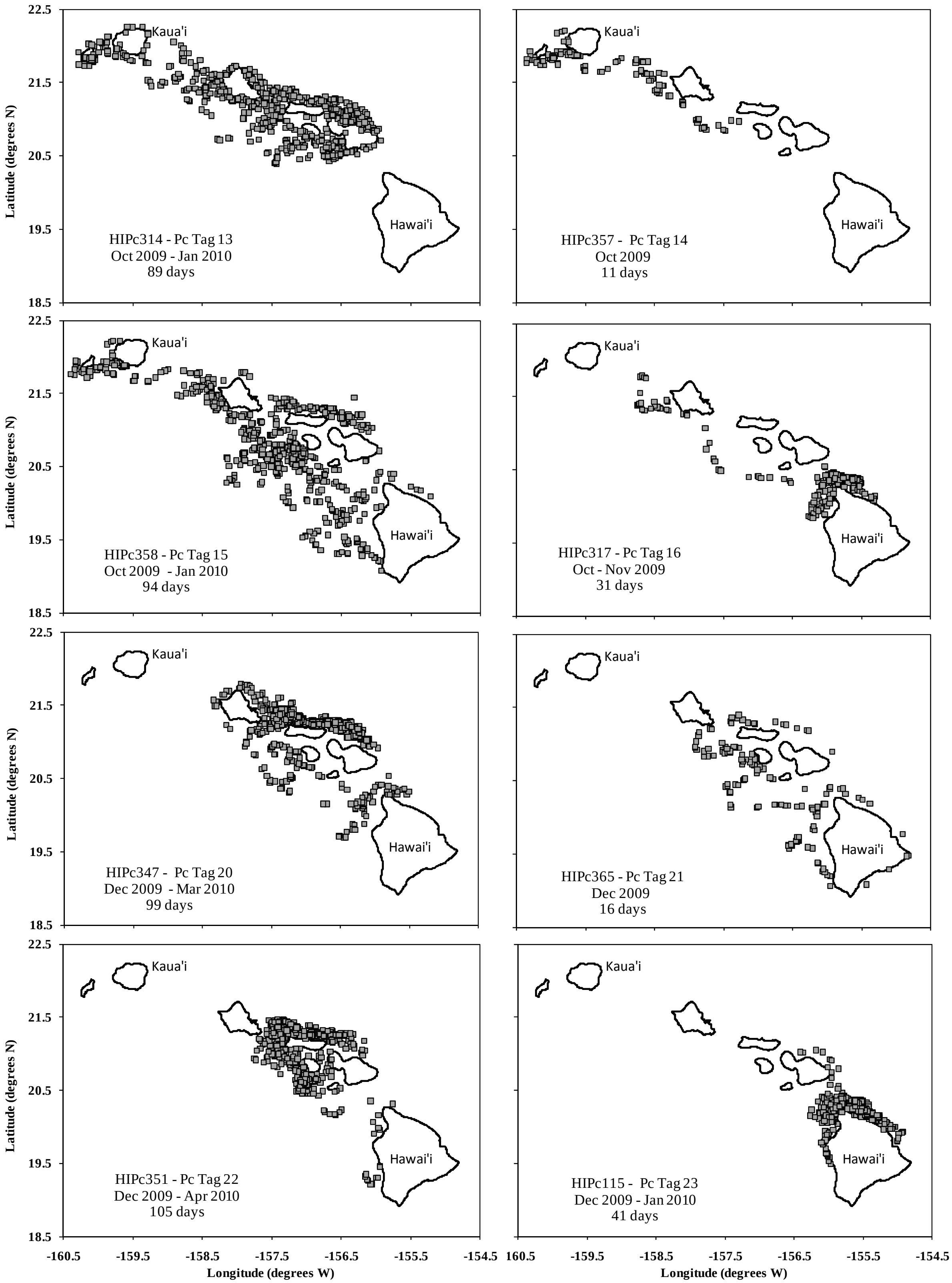

Figure 2. Maps of locations of satellite-tagged false killer whales. Top four – individuals tagged in October 2009 off O'ahu (fifth individual tagged in October shown in Figure 5). Bottom four – individuals tagged in December 2009 off Hawai'i.

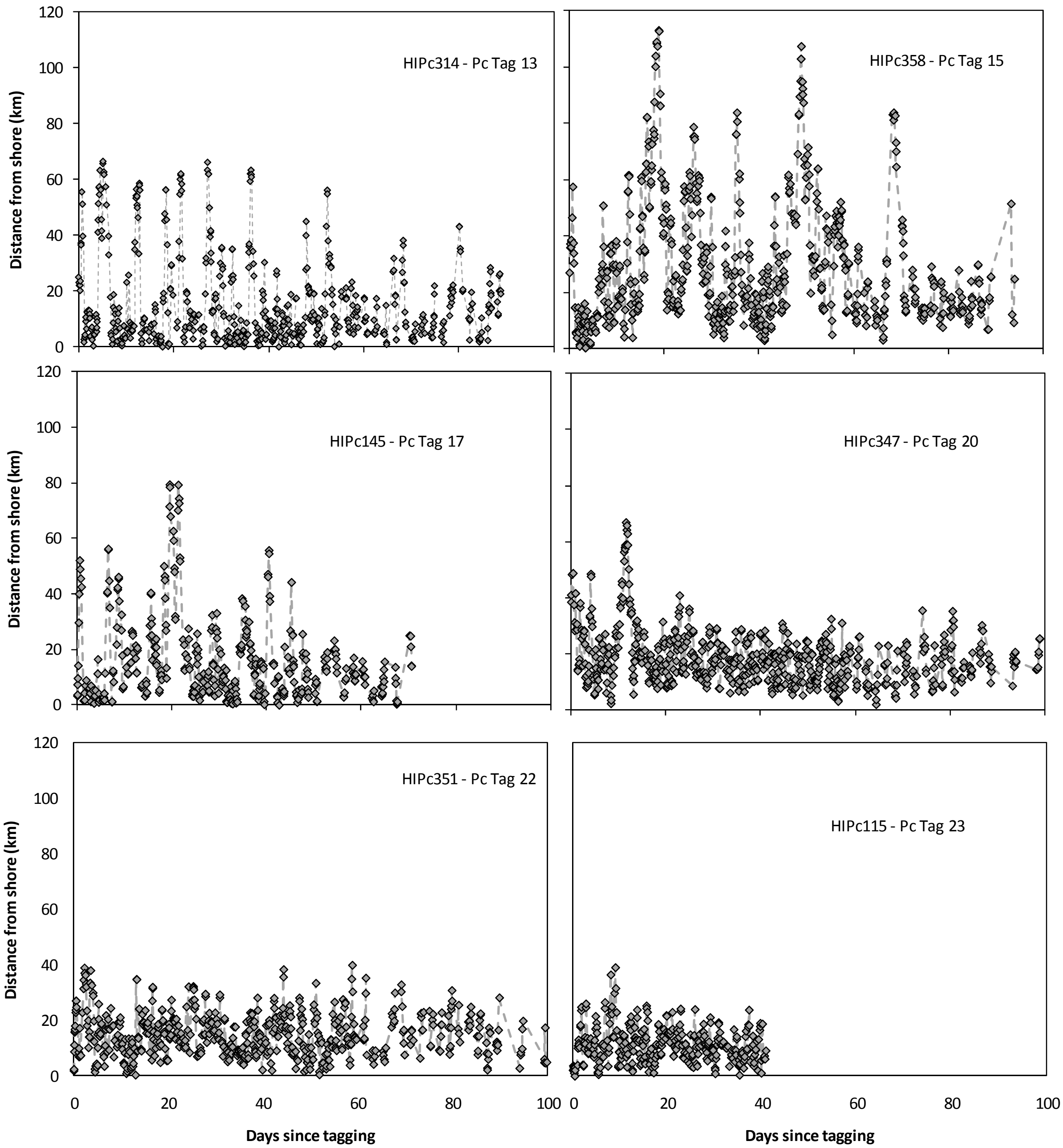

Figure 3. Distance from shore over time since tagging for six false killer whales for which 40 or more days of location data are available. X- and Y-axes scales are the same for comparative purposes. The first three individuals were tagged in October 2009 off O‘ahu, while the last three were tagged in December 2009 off Hawai‘i.

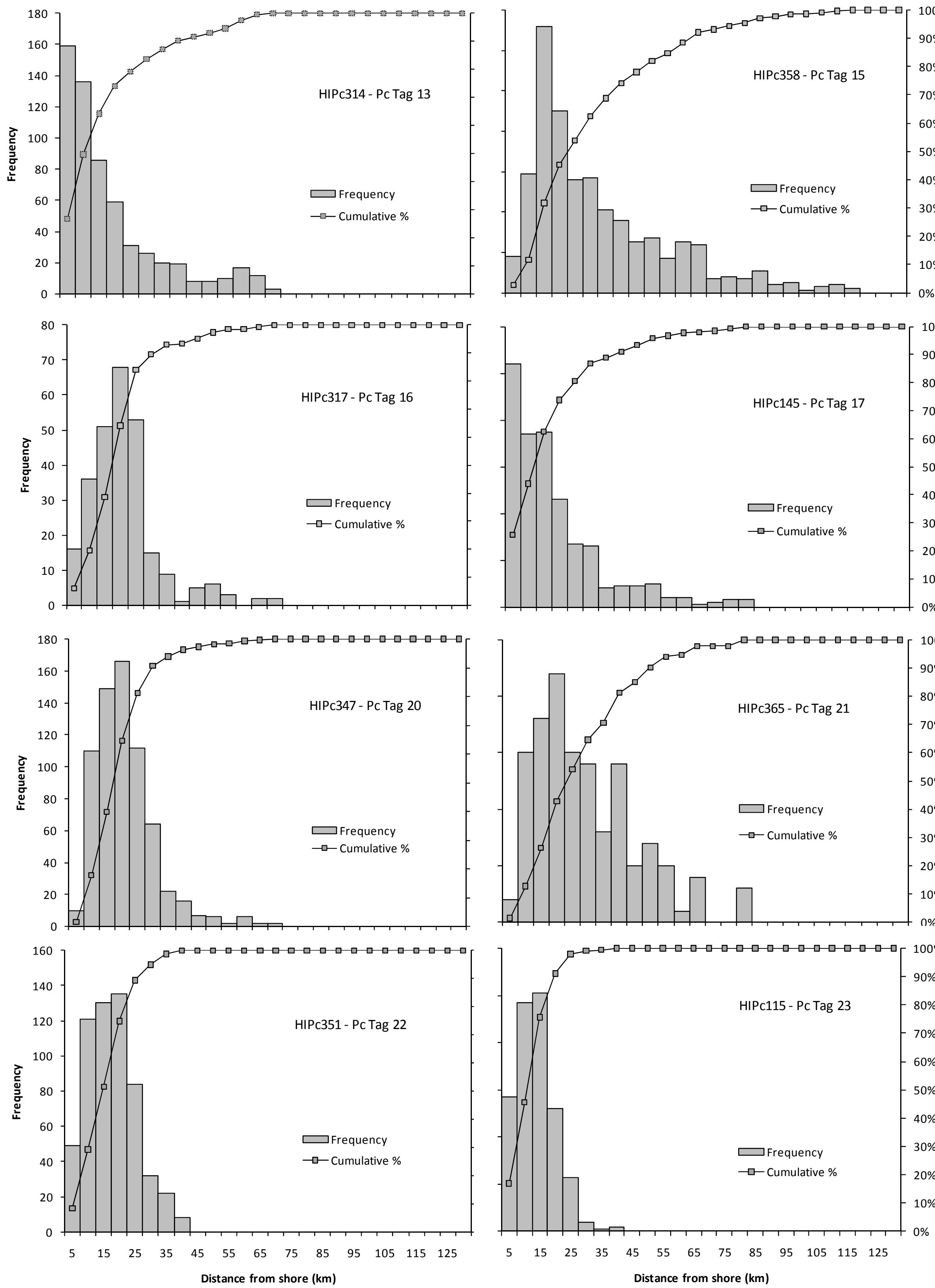

Figure 4. Cumulative distribution plots of time at distance from shore for false killer whales tagged in 2009 (excluding HIPc357 with 11 days of location data).

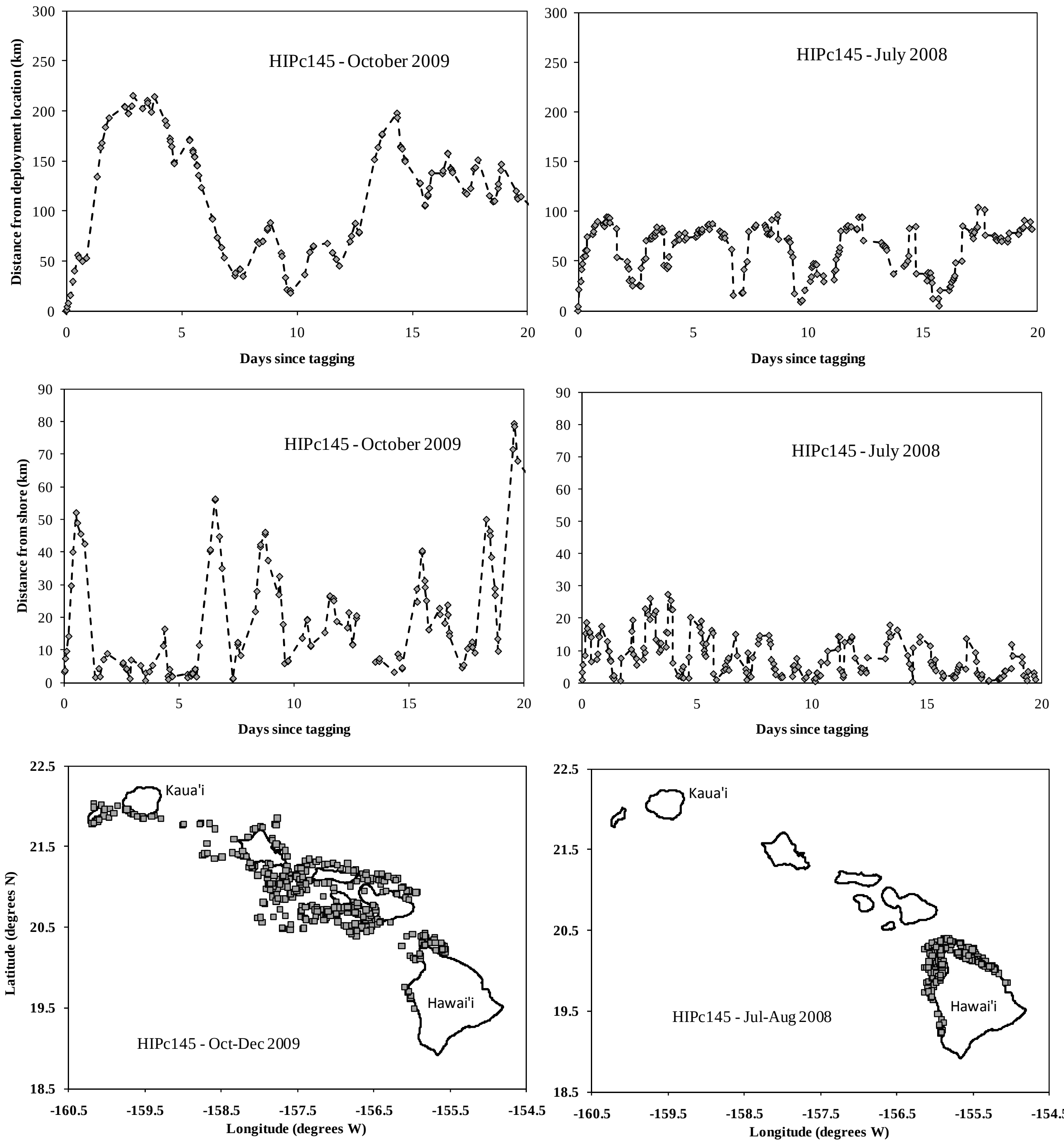

Figure 5. A comparison of movement patterns of false killer whale HIPc145 when tagged in October 2009 off O‘ahu (left column) versus when tagged in July 2008 off Hawai‘i (right column). The top two rows show only the first 20 days of data from the October 2009 tagging for comparison purposes, while the bottom row (maps) include all 71 days of movements from October 2009 and all 20 days of movements from July 2008.

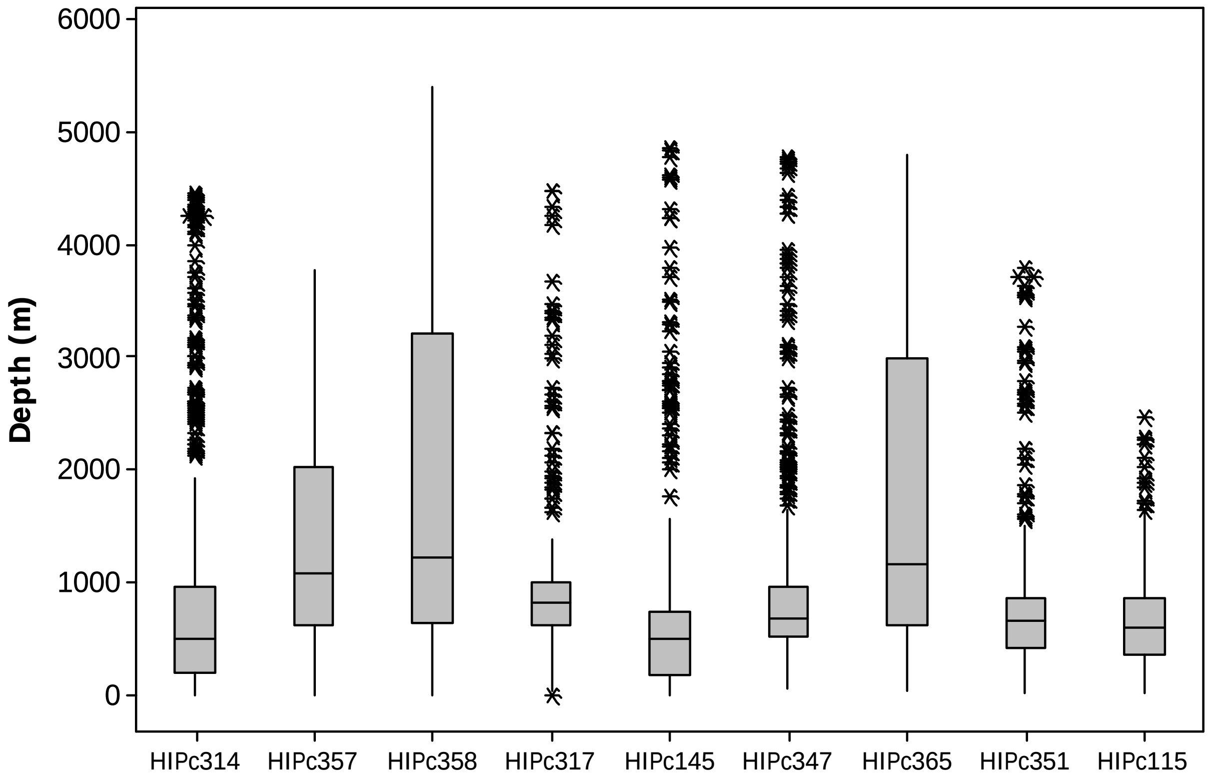

Figure 6. Box plots of depth by individual false killer whale tagged in 2009. Based on distance between individuals, only two pairs (HIPc357 and HIPc358; HIPc145 and HIPc115) were in close proximity (<20 km, see Figure 1, Table 3) over the duration of tag overlap. Only 12 days of locations were available for HIPc357, while 76 days of locations were available for HIPc358.

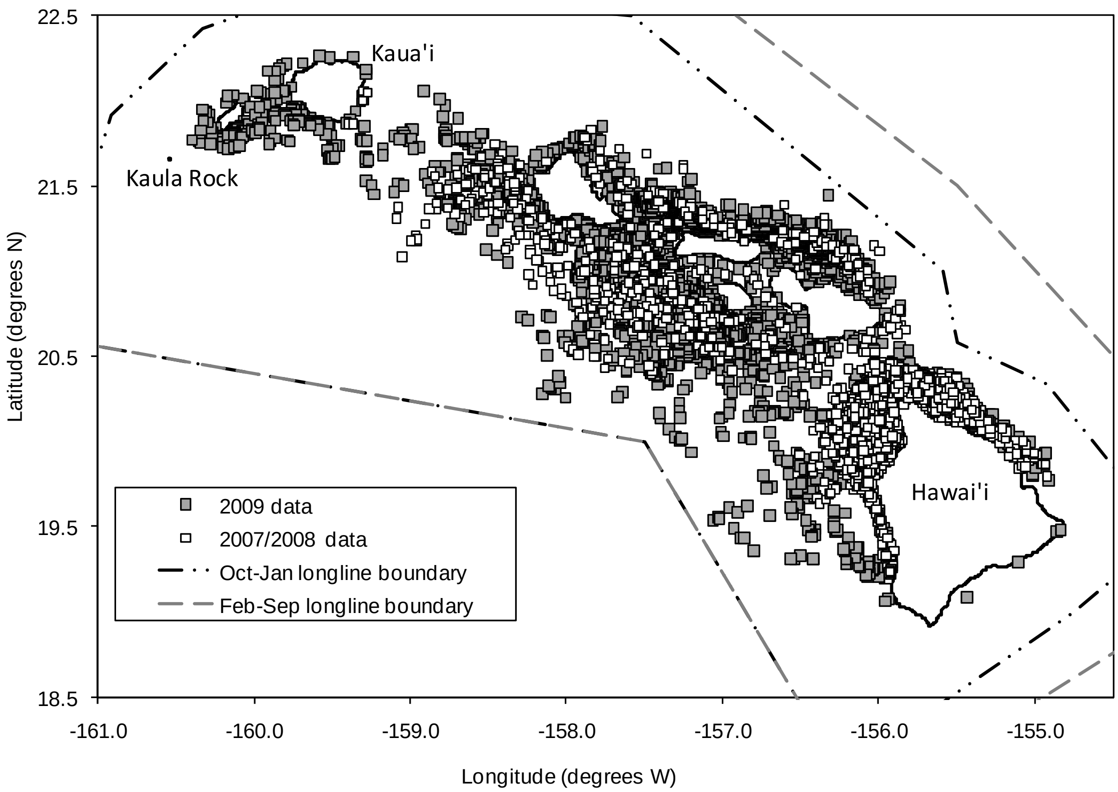

Figure 7. Map showing all locations of satellite-tagged insular false killer whales from 2009, as well as those tagged in 2007 and 2008 (from Baird et al. 2010a).