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NOTE

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Humpback whales (*Megaptera novaeangliae*) detected by autonomous Wave Glider in tropical deep seas between Hawaii and Western Pacific winter assemblies

James D. Darling[1] | **Beth Goodwin**[2] | **Adam J. Taufmann**[2] | **Murray G. Taylor**[2]

[1]Whale Trust, Makawao, Hawaii

[2]The Jupiter Research Foundation, Kamuela, Hawaii

Correspondence
Jim Darling, PO Box 243, Makawao, HI 96768.
Email: jimd367@gmail.com

North Pacific humpback whales migrate between high latitude feeding grounds around the Pacific Rim and winter breeding assemblies in tropical and subtropical waters (Nishiwaki, 1966; Rice, 1978). Winter assemblies occur off the coasts of: Mexico, including its offshore islands; Central America; the Hawaiian Islands; and island groups ranging from southern Japan, including Ogasawara and Okinawa, to the northern Philippines and the Marianas Islands (e.g., Acebes et al., 2007; Calambokidis et al., 2008; Darling & Mori, 1993; Hill et al., 2020; Lammers et al., 2011; Nishiwaki, 1966; Rice, 1978).

Two characteristics common to these locations, and breeding assemblies worldwide, are warm water (21.1–28.3°C) and relatively shallow seas (<200 m) over coastal shelves, banks, and atolls (Rasmussen et al., 2007). Satellite tag studies indicate that whales travel in a more or less direct course between feeding grounds and one of these nearshore, shallow, eastern, central, or western Pacific breeding assemblies in winter (Mate et al., 2007, 2019).

Recently, however, during an acoustic survey by an autonomous Wave Glider (WG) humpback whales were detected in tropical deep seas midway between the Hawaii and Mexico traditional assembly areas (Darling, Goodwin, et al., 2019). This unexpected finding raised questions about migratory behavior, as well as current abundance and distribution assessments based solely on inshore, shallow bank surveys.

That survey, east of Hawaii, was the first leg of a two-year Humpback Pacific Survey (HUMPACS) to search acoustically for humpback whales in the deep ocean, circa 20°N latitude, between the traditional assembly regions of Mexico, Hawaii, and Asia. Here, we report on the second leg of this survey, HUMPACS West, from Hawaii towards Asia undertaken from late December 2018 to mid-February 2019. It provided further evidence of humpback whale presence in mid-ocean basins at breeding season and latitude.

Detailed description of the Wave Glider and instrumentation is provided in earlier publications (Goodoni et al., 2018; Darling, Goodwin, et al., 2019) and is demonstrated at https://www.liquid-robotics.com/wave-glider/how-it-works/. The hydrophone, an Ocean Sonics icListen SB2-Ethernet digital hydrophone (sampling

rate range from 1 kHz to 512 kHz; frequency response 10 Hz to 100 kHz ±3 dB; sensitivity of −171 dBV re: 1 uPa), was mounted below the sub fuselage at −8.5 m (−28 ft).

One significant technical change from the first leg of the survey (HUMPACS East) was an increase in the separation of the hydrophone from the sub fuselage by an additional 7.6 cm, as well as a change in mounting material, which substantially reduced the impact of WG self-noise (float surface noise, rudder and wing assemblies, and water flow) on recordings (http://jupiterfoundation.org/current/category/HUMPACS+West).

At sea, recording (sampling rate of 32 kHz, 24-bit depth) was continual in one-minute WAV files stored in two separate 4 TB SSDs. That the position of the WG represented the approximate location of the calling whales is discussed in the paper presenting HUMPACS East (Darling, Goodwin, et al., 2019). To summarize, an estimate based on the source level of humpback whales 151–173 dB re 1 μPa at 1 m (Au et al., 2006), and presuming the calls were made at a typical shallow singer depth (<30 m), indicated detectable distance could range from 5.5 to 126 km (3–68 NM), the latter extreme distance only applicable if acoustic propagation conditions supported a first or second convergence zone.

Analysis was conducted by the Jupiter Research Foundation team (B.G., A.J.T., M.G.T.) with a combined 28 years of experience with humpback whale song off Hawaii as well as 2,000 hr on HUMPACS East recordings, and then reviewed by J.D.D. with 40 years of experience with humpback song in Hawaii and elsewhere. All recordings were analyzed manually using Raven Pro 1.5. Raw files were filtered for analysis using a low-pass Chebyshev Type I Infinite Impulse Response (IIR) filter of order 8 and then followed up with a bandstop filter to reduce glider rudder noise at frequency 325 Hz. Spectrographs of each 24 hr period were scanned visually for potential cetacean calls; when discovered, each call was listened to, and species identified when possible. Humpback whale song units were tabulated for each hour. Automatic Detectors or Classifiers were not used as faintness of the calls combined with self-noise of the glider made them likely to miss or misidentify calls (also see Baumgartner et al., 2013; Klinck et al., 2015).

The course, locations, detail, and results of the survey are summarized in Figure 1 and Table 1. The WG was launched from the island of Hawaii on December 26, 2018 and headed west at 20°N for 47 days and 2,911 km until February 11, 2019 when a control malfunction forced its retrieval. During this second leg of the survey, a total of 1,128 hr of audio recording was collected.

Humpback whale song was detected on 10 of the 47 days. As expected, song was detected continually during the first three days after the December 26 launch as the WG made its way through the Hawaii breeding ground (and within 48 km of Hawaii shores), where song is ubiquitous. Then after no detections during December 29–31, 2018, song was heard during one day, January 1, 2019, 363 km to the west of Hawaii (Figure 1, Table 1).

Following this one-day detection, on January 1, the WG traveled 23 days and 1,408 km (from 19.89°N, 159.72°W to 20.16°N, 172.38°W) without hearing humpback whales. Then, beginning on January 24, 2019, 1,728 km west of Hawaii (20.16°N, 172.38°W), there were six days of near continuous humpback whale song though January 29, 2019 and 1,974 km west of Hawaii (19.86°N, 174.93°W) (Figure 1, Table 1). During this period of clear humpback whale presence, the Wave Glider traveled 246 km on its westbound course, averaging 1.5 knots. After this period, and for the next 14 days and 937 km of travel further west to the end of the survey humpback whales were not detected.

Well over 1,000 distinct humpback whale calls (song units, some in phrases) were identified during the six-day encounter, with whales heard up to 23 hr in a 24 hr time period (Table 1). It is not possible to estimate numbers of whales but in one case, on January 29, 2019, our most westerly detection, overlapping calls indicated more than one whale in the region.

Notable are the extended periods without clear humpback whale detections before and after the six days of song detection. Other cetaceans, including minke whales (*Balaenoptera acutorostrata*), sperm whales (*Physeter catodon*), and smaller odontocetes were recorded throughout the survey, including the periods when humpback whales were not heard. Importantly, during these periods, sounds were recorded that conceivably could have been humpback whales but were too distant to identify with confidence.

Song phrases recorded offshore were markedly similar to those in the 2019 song from Hawaii sampled from January to April off Maui (J.D.D., unpublished data) as well as by the WG as it left Hawaii to begin the offshore survey. Spectrograph comparisons are provided in Figure 2, with corresponding audio in the Supporting Information section. Three phrases, which were components of the Hawaii song, were identified in the offshore recordings. This

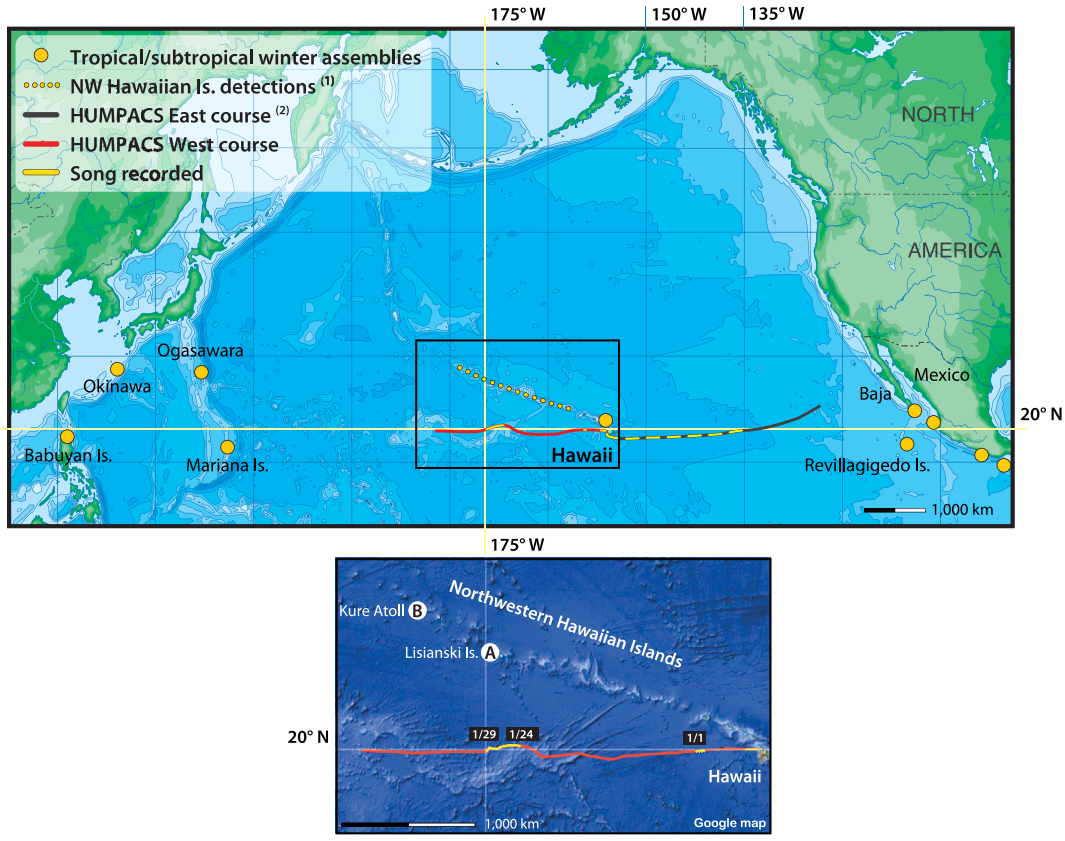

FIGURE 1 Large scale (approximate) routes of the wave glider in the HUMPACS West survey (December 26, 2018 to February 11, 2019) and HUMPACS East survey (January 16–March 13, 2018, to turnaround; see Darling, Goodwin et al., 2019) in relation to known tropical or subtropical winter assemblies including Northwestern Hawaiian Island presence (Johnstone et al. 2007; Lammers et al., 2011). HUMPACS survey humpback whale song detections are shown in yellow. **Inset:** Exact route of HUMPACS West and song detections with dates. Also indicated are the locations of *westernmost* published humpback whale acoustic detections in the Northwestern Hawaiian Islands at (A) Lisianski Island (Johnstone et al., 2007) and (B) Kure Atoll (Lammers et al., 2011).

[1]From Johnstone et al 2007; Lammers et al., 2011

[2]From Darling, Goodwin et al., 2019.

does not mean other phrases in the Hawaii song were not present, likely just not clear enough to be identified in this circumstance. Despite the general faintness (i.e., distance from WG) of the offshore song detections, with the signal intermittent at times, multiple instances of these recognizable Hawaii song units and phrases were recorded over the six days from January 24–29, 2019. The best audible segment was over a 20 min period on January 27, 1,915 km west of Hawaii (20.06°N, 174.09°W). All three phrases were heard within that time period; that is, the singer changed from one phrase to another during that 20 min as occurred in the concurrent Hawaii song.

This encounter in deep ocean basin adds to evidence of a tropical offshore distribution of North Pacific humpback whales at the same time as they are inshore in known traditional winter assemblies. The context of the offshore detections in relation to current knowledge needs to be determined with further exploration.

On the north-south axis, the location of this encounter (from approximately 20°N, 172°W–20°N, 175°W) is near the same longitude and about 1,000 km further south, as the *western-most* humpback whale acoustic detections in the Northwestern Hawaiian Islands, at Lisianski Island at 26°N, 174°W in 2007 (Johnston et al., 2007), and Kure Atoll at 28°N, 178°W in 2009 (Lammers et al., 2011) (Figure 1 inset). The Northwestern Hawaiian Islands are a series

TABLE 1 Date, duration over the 24-hour period, the number, location, ocean depth and distance from Hawaii of humpback whale call detections. Location and distance from Hawaii approximate: taken at 16:00 UTC (6:00 a.m. HST) each day.

	Call detections[a]		Location		Depth[c]	Distance west of Hawaii
Date (2019)	Duration hr:min	No.	Latitude °N	Longitude °W	Meters	Kilometers/nautical miles
Jan 1	10:53[b]	146	19.89	159.72	2,525	363/196
Jan 24	2:09	114	20.16	172.38	1,156	1,728/933
Jan 25	17:05	21	20.22	173.23	2,758	1,806/975
Jan 26	19:24	81	20.18	173.73	2,750	1,852/1,000
Jan 27	22:51	505	20.06	174.09	2,400	1,915/1,034
Jan 28	23:36	600	20.01	174.51	2,200	1,924/1,039
Jan 29	12:21	108	19.86	174.93	2,300	1,974/1,066

Note. As expected, song was also heard on the first three days (December 26–28, 2018) after launch from 0 to 48 km (26 nm) from the Hawaii shore, not included in the table. The sea surface temperature during the days that humpback whales were detected ranged from 25.99°C to 27.05°C.

[a]Only detections considered to be humpback whales with high confidence are included in this table. The Duration column gives the length of time over which humpback whales were detected during that 24 hr period. The No. column gives the number of calls heard during that time frame.

[b]Example: on January 1, 2019, humpback whales were first detected at 1:55:18 UTC and the last detection was at 12:48 UTC, a time period of 10 hr and 53 min. During that period a total of 146 separate calls were heard.

[c]Average depth over the 24 hr period.

of shallow banks, atolls, and islands, which arch north and west of the main Hawaiian Islands for approximately 2,000 km to Kure Atoll. It is presumed that humpback whales in the Northwestern chain are drawn to the shallow water habitat as either a route to, alternative for, or continuum of, the main Hawaiian Island assembly (Johnston et al., 2007; Lammers et al., 2011). These deep-water detections directly south of the Northwestern chain indicate humpback whale presence in this region is not necessarily tied to shallow waters.

From the east-west perspective, the detections reported are on the 20°N latitude band that generally transects the winter assemblies in the North Pacific. The recorded whales were about one-third the distance between Hawaii and the western Pacific winter assembly areas in Ogasawara, (1,915 of 6,213 km; Darling & Mori, 1993) or the Mariana Islands, (1,915 of 6,110 km; Hill et al., 2020) (Figure 1). This detection area along 20°N to the west of Hawaii, albeit not as continuous, is a mirror image to the results of HUMPACS East leg, where whales were found at the same latitude half the distance from Hawaii to Mexico (Darling, Goodwin, et al., 2019). The notion of a circa 20°N band of humpback whale winter habitat across the tropical Pacific, including the nearshore shallow water assemblies, seems increasingly plausible.

Likely explanations for the humpback whale detections include: (1) whales traveling to, from, or between either known nearshore winter grounds or, conceivably, *unknown* nearshore or shallow water winter grounds amidst atoll or sea mount habitat in the tropical central-western Pacific; or (2) evidence of an entirely offshore, deep water assembly at breeding ground latitudes.

As discussed in the HUMPACS East report (Darling, Goodwin, et al., 2019), if whales were traveling to or from feeding grounds, these detections would indicate a significant low latitude, east-west component to the migration (for example, to be the explanation for these detections, whales traveling from Russia to Hawaii would travel south until 20°N and then turn east to Hawaii). However, this seems inconsistent with known satellite tag routes, where whales generally appear to follow the straightest course to the destination (Mate et al., 2007, 2019). Travel within season between traditional assembly areas in the western Pacific and Hawaii cannot be ruled out, as interchange of whales between Japan, Philippines, and Hawaii has been documented; however, to date, not in the same season (Calambokidis et al., 2008; Darling & Cerchio, 1993; Salden et al., 1999).

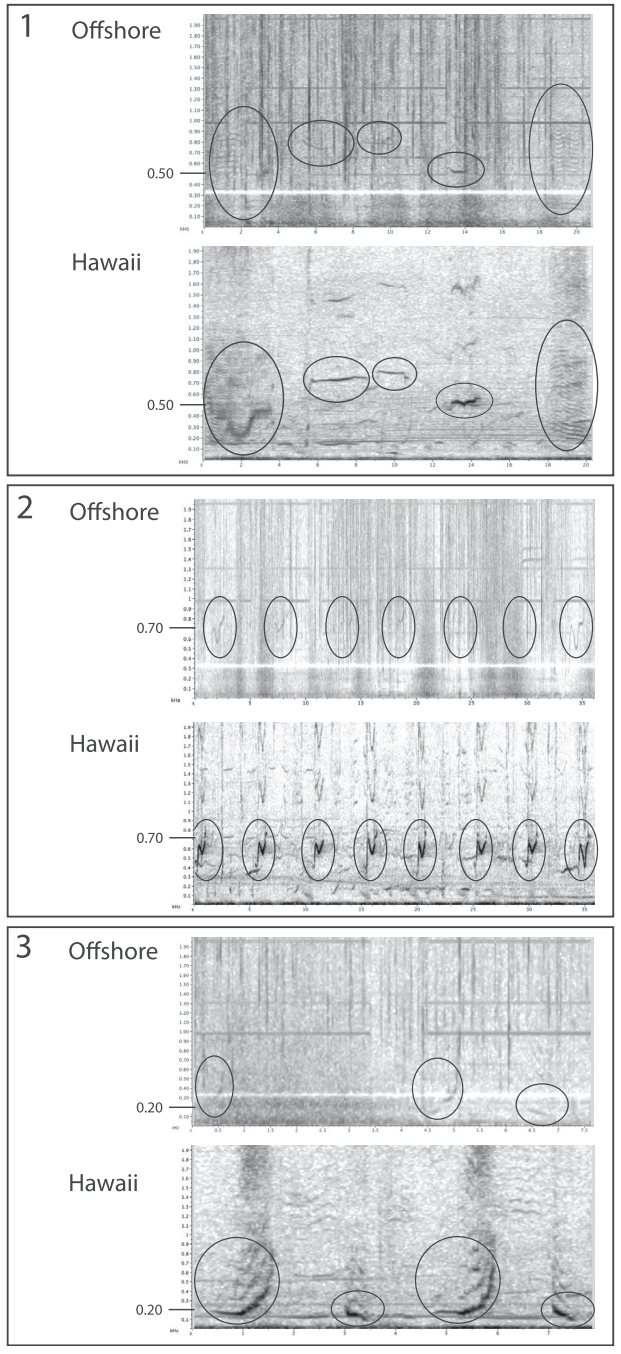

FIGURE 2 Humpback whale song phrases recorded during the HUMPACS West survey (as in Figure 1, on January 27, 2019) compared to those recorded in Hawaii in 2019. Examples 1–3 are three different phrases that comprise three themes of the song. (Spectrographs, all Hann window, 50% overlap, FFT/DFT Example 1: Offshore 2,048, Hawaii 8,192; Example 2: Offshore 1,042, Hawaii 8,192; Example 3: Offshore 512, Hawaii 4,096).

There is a myriad of atolls and shallow (<200 m) seamounts or banks in the central-western tropical North Pacific. While the survey transect was not over any of these (the shallowest area crossed on the route was 1,158 m), it is possible that the whales reported here in deep ocean were en route to shallow water habitat surrounding one or

more of these features further to the south. Anecdotal reports of humpback whales near Johnston Atoll (16.73°N, 169.53°W), approximately 1,500 km west and south of Hawaii, have been circulating for some years. However, we were unable to verify any of these reports, and a survey in the region in March 2006 produced no sightings (Johnston et al., 2007). Our closest humpback whale detection to Johnston Atoll was on 24 January 2019 approximately 478 km to the northwest (at 20.20°N 172.69°W). Similarly, we were unable to find any confirmed reports of humpback whales around other potential habitat in the western-central tropical North Pacific. However, these assessments are far from definitive: no comprehensive survey of the region has been undertaken, and it is clear humpback whales utilize similar habitat for breeding activities both in the North Pacific (Johnston et al., 2007; Klinck et al., 2015; Lammers et al., 2011) and the South Pacific (Derville et al., 2018; Garrigue et al., 2015).

An entirely offshore seasonal assembly as an explanation requires a change in thinking about critical breeding habitat for this species, which currently is defined as a combination of shallow (<200 m) banks *and* a sea water temperature from 21.1°C to 28.3°C (Rasmussen et al., 2007). The locations of humpback whales reported here met the temperature requirement (26°C–27°C), but not the depth characteristic. It is presumed shallow water habitat optimizes nurturing and survival of young, but this has not been tested, and there is no suggestion of a role for shallow water in adult mating activity. Other balaenopterids appear not to require shallows for successful reproduction. Perhaps too much emphasis has been placed on geographic location for much of humpback whale breeding behavior.

Countering any idea of a population entirely independent from other North Pacific humpback whale populations is the similarity of song phrases to those from Hawaii. And, as song phrases can be shared ocean-wide, this similarity does not rule out a connection between these offshore whales and any of the other known North Pacific humpback whale assemblies (Acebes et al., 2007; Cerchio et al., 2001; Darling & Mori, 1993; Darling, Acebes, et al., 2019; Payne & Guinee, 1983).

A comprehensive study of the structure of populations, levels of abundance, and status of humpback whales in the North Pacific (SPLASH) was undertaken in 2004–2006 (Calambokidis et al., 2008). Within this study was a prediction of "missing wintering areas not previously described." This was based on the observation that humpback whales identified off the Aleutian Islands and in the Bering Sea were not well represented on any of the sampled wintering areas. The detections here in the central-western Pacific, as well as those in eastern Pacific (Darling, Goodwin, et al., 2019), and indeed along the Northwest Hawaiian Islands (Lammers et al., 2011), indicate that there were, as predicted, winter distributions of humpback whales not sampled in that study.

There is one further note relating specifically to the the main Hawaiian Islands. To date all studies and assessments of "Hawaii" humpback whales have been undertaken on the shallow banks surrounding or joining these Islands. However, this survey and other recent studies indicate that humpback whale distribution extends into deep water well beyond the nearshore area. Autonomous vehicle surveys have shown that humpback whales were "continuously present" in (1) December 2014 and January 2015 up to 330 km *southwest* of Hawaii (Klinck et al., 2015), (2) in January and February 2018 *east* of Hawaii well out into mid-ocean basin (HUMPACS East) (Darling, Goodwin, et al., 2019), and (3) in this study in January 2019 to the *west* of Hawaii up to 48 km and again at 370 km offshore. The relationship and/or interactions between the whales orbiting Hawaii in deep water, and the familiar Hawaii inshore whales is not known. However, if all are part of one group, these observations raise the possibility that studies on the nearshore shallow banks of the Hawaiian Islands may not adequately sample or assess the numbers and behavior of whales in the "Hawaii" assembly.

It is clear that our understanding of distribution, movements, and behavior of humpback whales in the North Pacific is incomplete. Evidence is mounting that humpback whales are distributed in tropical deep ocean basins at the same time as the traditional assemblies in shallow nearshore breeding grounds. The extent and purpose of this offshore occurrence is currently unknown. To date this offshore distribution has not been considered in management or conservation assessment.

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AUTHOR CONTRIBUTIONS

James Darling: Conceptualization; formal analysis; investigation; methodology; validation; writing-original draft; writing-review and editing. **Beth Goodwin:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-review and editing. **Adam Taufmann:** Data curation; formal analysis; investigation; methodology; resources; writing-review and editing. **Murray Taylor:** Data curation; formal analysis; investigation; methodology; resources; writing-review and editing.

ORCID

James D. Darling https://orcid.org/0000-0001-5514-4894

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SUPPORTING INFORMATION

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

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