Fin whale tracks recorded by a seismic network on the Juan de Fuca Ridge, Northeast Pacific Ocean

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Fin whale calls recorded from 2003 to 2004 by a seafloor seismic network on the Endeavour segment of the Juan de Fuca Ridge were analyzed to determine tracks and calling patterns. Over 150 tracks were obtained with a total duration of ~800 h and swimming speeds from 1 to 12 km/h. The dominant inter-pulse interval (IPI) is 24 s and the IPI patterns define 4 categories: a 25 s single IPI and 24/30 s dual IPI produced by single calling whales, a 24/13 s dual IPI interpreted as two calling whales, and an irregular IPI interpreted as groups of calling whales. There are also tracks in which the IPI switches between categories. Call rates vary seasonally with all the tracks between August and April. From August to October tracks are dominated by the irregular IPI and are predominantly headed to the northwest, suggesting that a portion of the fin whale population does not migrate south in the fall. The other IPI categories occur primarily from November to March. These tracks have slower swimming speeds, tend to meander, and are predominantly to the south. The distribution of fin whales around the network is non-random with more calls near the network and to the east and north.
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I. INTRODUCTION

Fin whales (*Balaenoptera physalus*) are an endangered baleen whale with a global distribution (Mizroch *et al.*, 2009). Passive acoustic methods have been widely used to identify their call types and calling patterns (e.g., Hatch and Clark, 2004; Watkins *et al.*, 1987; Watkins, 1981). The most common call produced by fin whales is a down-swept 20 Hz pulse that is ~1 s in duration and typically ranges from ~18 to ~23 Hz (Watkins *et al.*, 1987; McDonald and Fox, 1999). Other calls include a 15 to 18 Hz narrow-band backbeat (Hatch and Clark, 2004), a higher frequency down-swept pulse at frequencies up to 35 Hz (Thomson and Friedl, 1982), and a 135 Hz upsweep (Watkins *et al.*, 1987). The number of calls fin whales produce per day has been reported to vary seasonally with more calls in winter (Sirovic *et al.*, 2007; Watkins *et al.*, 1987; Moore *et al.*, 1998), diurnally with more calls at night (Watkins *et al.*, 1987; Oleson, 2005), and inter-annually (Stafford *et al.*, 2009). The 20-Hz calls commonly occur in stereotyped sequences or songs that are attributed to males (Croll *et al.*, 2002) and can last for over a day (Delarue *et al.*, 2009). Songs can be comprised of a single call repeated at a fixed interval, or doublets and triplets of closely spaced calls separated by a longer interval (Watkins *et al.*, 1987, Oleson 2005). Songs can be used as a proxy for population identification because they vary geographically (Hatch and Clark, 2004; Delarue *et al.*, 2009; Castellote *et al.*, 2011) while showing little intra- or inter-individual variation within a geographic region (Delarue *et al.*, 2009).

Migratory habits of fin whales are difficult to observe and quantify due to the pelagic nature of their habitat. With hydrophones researchers can analyze seasonal variability (Delarue *et al.*, 2009), conduct detection range modeling (Stafford *et al.*, 2007), and examine population density (McDonald and Fox, 1999). Based on whaling data and fin whales that were tracked using radio tags, at least a portion of the Northeast Pacific population migrates southward in winter (Mizroch *et al.*, 1984). Acoustic records indicate that a portion of the fin whale population remains in the Northeast Pacific throughout the winter and presumably feeds during this period (Stafford *et al.*, 2009). These results may indicate that only portions of the population migrate (Payne and Webb, 1971) and indicate the need for more information on fin whale movements.

Fin whale vocalizations at frequencies near 20 Hz are detectable using ocean bottom seismometers (OBSs) designed for earthquake studies. Two previous investigations (McDonald *et al.*, 1995; Rebull *et al.*, 2006) used data from relatively short duration OBS experiments to demonstrate the potential of OBS networks to track fin whales. In this study fin whale tracks and calling patterns are obtained over one year with data from a local seismic network on the Endeavour segment of the Juan de Fuca ridge. The results are used to investigate patterns in calling and movement.

II. METHODS

A. Seismic network

This study uses data from a local seismic network that was deployed on the Endeavour Segment of the Juan de Fuca ridge located 250 km offshore of Vancouver Island in the Northeast Pacific Ocean (Fig. 1). The central portion of the Endeavour segment is delineated by a topographic high that is cut by a 100- to 200-m-deep and 1-km wide axial valley that hosts 5 major hydrothermal vent fields. Depths in the region range from 2100 to 2800 m and the ridge flanks are characterized by 300-m-high ridge parallel abyssal hills.

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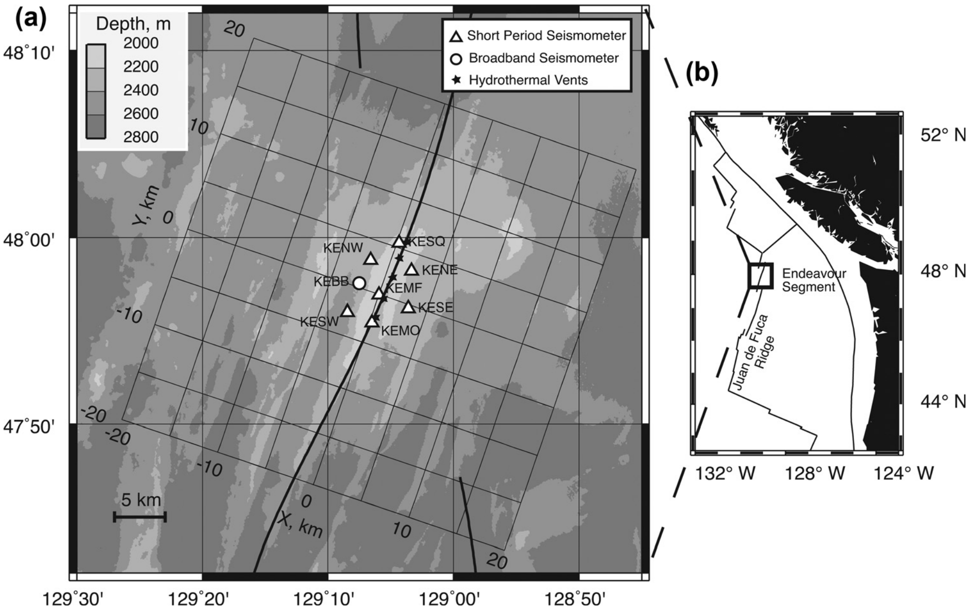

FIG. 1. (a) Bathymetric map showing the configuration of the experiment. The position of the spreading center is shown by solid bold lines and hydrothermal vent fields by black stars. The seismic network is comprised of seven short period seismometers (open triangles) and one buried broadband seismometer (open circle), which are labeled with the station name. Whales were tracked within a square *x-y* grid (faint lines) centered on the seismic network with the *y*-axis aligned with the ridge axis. (b) A regional map showing the location of the study area and tectonic plate boundaries.

The seafloor near and to the west of the ridge axis consists of rough basaltic topography with a thin sediment cover in the topographic lows while to the east extensive turbidite deposits extend within about 6 km of the ridge.

The eight station seismic network (Fig. 1) was deployed around the vent fields for three years starting in August 2003. The network aperture was 10 km along the axis and 6 km across the axis with a station spacing of 3 km (Wilcock *et al.*, 2009). Seven of the stations were three-component MBARI/GEOSense seismometers (Stakes *et al.*, 1998) with a flat response from 1 to 90 Hz that was sampled at 128 Hz. The eighth station was a three-component MBARI Guralp broadband seismometer (Romanowicz *et al.*, 2006) with a flat response from 2.8 MHz to 50 Hz that was sampled at 50 and 100 Hz. The stations were installed below the seafloor using remotely operated vehicles to ensure good coupling and recorded continuously with data retrieval each summer. All the stations recorded good data in the first year but in subsequent years instrument failures reduced the number of usable stations to 5 to 7 (Weekly *et al.*, 2013). This study is limited to the first year of data.

B. Whale tracking

The fin whale detection and location method is described in detail by Wilcock (2012). The ratio of root-mean-squared (rms) amplitudes in running short- and long-term boxcar windows is used to detect impulsive arrivals on each channel. Potentially locatable events are found by grouping arrivals detected within 2.5 s of one another on at least eight channels and four OBSs (Fig. 2). If more than half of the arrivals have more spectral energy in the 15 to 35 Hz band than the 5 to 15 Hz band, the event is identified as a whale call. Direct and multiple arrivals are picked by finding peaks in the instantaneous amplitude that exceed background noise by a factor of 2 and are at least 1 s away from higher peaks.

To locate whale calls a grid search is used to systematically search spatial locations with different assumptions about the number of multiples associated with each arrival. The RAY two-dimensional ray-tracing software (Bowlin *et al.*, 1993) is used to calculate travel times using a depth-dependent water velocity model for the region and taking into account the seafloor bathymetry along the profile between each station and grid point. The method finds the grid point that minimizes the rms travel time residual while fitting an acceptable number of arrivals. The formal position uncertainty is typically 0.5 km for locations inside the network, increasing to up to several kilometers at the maximum location range of 15 to 20 km (Wilcock, 2012).

For calls more than 5 to 10 km outside the network, the direct arrival has a low amplitude and is often not picked; for such calls the algorithm sometimes mislocates calls by systematically assigning one too few multiples to each

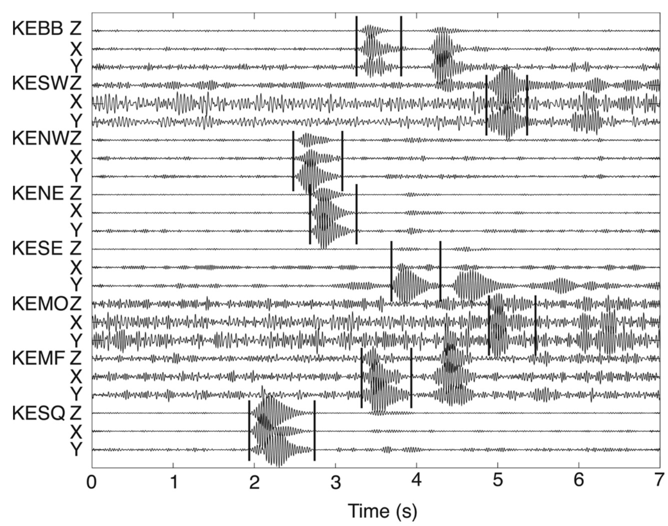

FIG. 2. An example of a call from a fin whale in the northern part of the seismic network. A high-pass 5 Hz filter has been applied and the records have been adjusted to equal maximum amplitude for each seismometer. The labels show the station name (Fig. 1) and geophone orientation with the *X* and *Y* channels horizontal and the *Z* channel vertical. The direct arrivals are demarked with vertical bars and the first and sometimes second water column multiples are also often visible.

arrival. The algorithm can also mislocate calls if arrivals from two calling whales overlap or if the signal-to-noise ratio is poor. To identify tracks we inspect the locations and the seismic data manually. If a minimum of 30 locations occurring over at least half an hour form a clear track that travels a minimum resolved distance of 2.5 km, a smooth path is input manually through these locations. The smooth path is then used for a second iteration of the grid search that requires solutions to lie near the path.

C. Calling patterns

Because the tracking algorithm does not detect and locate every call, a spectral detection method was developed to analyze the scale calling patterns along each track. Each call sequence is inspected on multiple stations and the station/channel combination with the highest signal-to-noise ratio is used to detect calls. A spectrogram is calculated with a 128 point Fourier transform, a Hanning window, and a 98% overlap [Fig. 3(a)]. A modified spectrogram in decibels is created by subtracting a threshold set to two standard deviations above the mean decibel level in the 15 to 35 Hz whale band and zeroing all negative values [Fig. 3(b)]. Times for possible whale arrivals are found by summing the modified spectrogram between 15 and 35 Hz at each time sample and finding peaks.

If the original spectrogram for a detection contains more energy in the 5 to 15 Hz band than in the 15 to 35 Hz band, the peak is interpreted as an earthquake and discarded. The remaining peaks are classified as whale calls if two criteria are met: (1) The amplitudes exceed a detection threshold set to 25% of the largest peak in a 10-min window and (2) the peak is spaced 7 s from all larger peaks to eliminate multi-path arrivals. The algorithm fails when earthquake energy swamps the whale calls or during intervals with a low signal-to-noise ratio, where it triggers on background noise likely caused by distant fin whales. During these periods an analyst manually adjusts the detection threshold. The performance of this method was evaluated for a subset of data comprising 2400 calls on portions of 10 tracks by comparing detections to visual identifications by the analyst; there were no false detections and only 0.7% of the calls were missed.

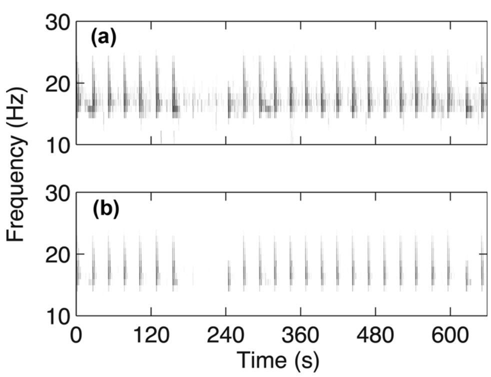

FIG. 3. (a) Example spectrogram from 24 October 2003 (128 point Fourier transform, a Hanning window, and a 98% overlap) showing fin whale calls received on the network. (b) A modified spectrogram of the same data created by converting to decibels, subtracting a threshold set to two standard deviations above the mean decibel value in the 13 to 35 Hz frequency band and zeroing all negative values.

The weighted mean and standard deviation of the calls frequency are calculated from the modified spectrogram for each call. Backbeat calls (Hatch and Clark, 2004) are present on many tracks but efforts to identify them automatically based on their lower frequency and smaller standard deviation of frequency proved unreliable because they showed a high level of variability. Instead, backbeats were identified manually for a representative subset of 20 whale tracks based on comparing the mean frequency and bandwidth of adjacent calls.

Following the terminology of Watkins *et al.* (1987), the inter-pulse interval (IPI) is calculated as the time spacing between the start of two successive calls in a sequence. Since most call sequences include notes with different frequency, the IPI is different from the inter-note interval used by some researchers which measures the time spacing between two successive calls of the same frequency (Hatch and Clark, 2004; Castellote *et al.*, 2011). Watkins *et al.* (1987) define longer IPIs lasting from 1 to 20 min and 20 min to 2 h as rests and gaps, respectively, and groupings of IPIs separated from other groupings by at least 2 h as bouts. To be consistent with this terminology all pairs of tracks falling within 2 h of each other were examined. If the two segments had similar IPI patterns and call frequencies, and swimming speeds and directions that were consistent with each other and with the spacing between the tracks, they were merged into a single track.

For each track, histograms were created of the call frequency, IPI, rest duration and rest spacing, and an average swimming speed and meander parameter were calculated. The meander parameter is defined as the ratio of the total distance along the smoothed path to the net distance traveled; a value of 1 would indicate a straight path. To identify relatively straight and fast tracks, a track is defined as transiting if its speed is >4 km/h and its meander parameter is <1.25.

If the IPI histogram indicated an irregular pattern of calls, the seismic record sections were inspected to search for variations between successive calls in the relative arrival times and amplitudes at different stations that would indicate that the track was obtained during an interval when there were calls from a whale in a different location. Tracks or portions of tracks that were corrupted by off track calling were excluded from the detailed analysis of calling patterns.

Figure 4 shows results for one example whale track. This whale is tracked [Fig. 4(a)] for 22 h as it swims with an average speed of 1.3 km/h along the ridge axis from the north to the south with a meander parameter of 1.7. The spectral characteristics of the calls from a 10 min segment [Fig. 4(b)] show mostly 19 Hz calls. Two backbeats are visible at 240 and 620 s and one resting interval from $\sim$140 to 240 s. The IPI histogram [Fig. 4(c)] shows little variation from its 25 s peak, with almost all the calls from this track in the 24 to 26 s bins. The histogram of call frequency [Fig. 4(d)] peaks at 19 Hz with all calls between 16 and 20 Hz. The backbeat calls have lower frequencies but do not create a separate peak.

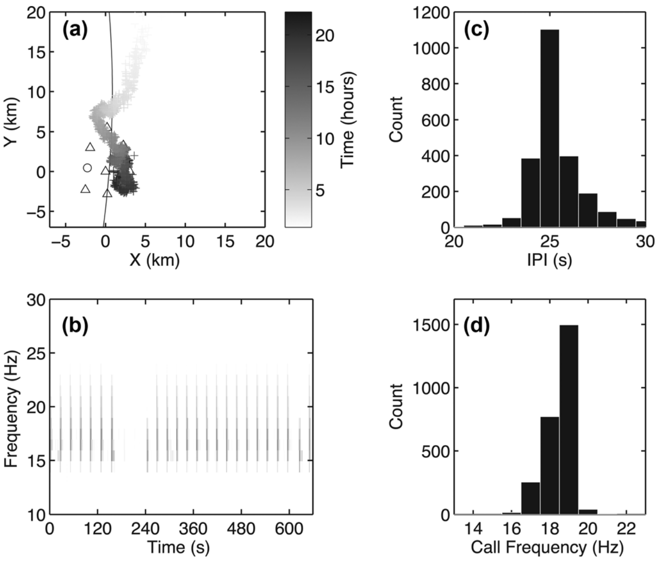

FIG. 4. (a) Example from 24 October 2003 of a 25 s single IPI fin whale track with locations shown by pluses shaded by time with light gray at the start of the track and dark gray at the end. The origin of the plot coincides with the center of the network and the *y*-axis for the plot is aligned with the mid-ocean ridge axis (Fig. 1). The seismic stations of the network are shown by open symbols. (b) Modified spectrogram for 650 s of data from the northernmost station. (c) Histogram showing distribution of IPI. (d) Histogram showing the distribution of call frequencies.

III. RESULTS

The complete analysis of the seismic data from August 2003 through July 2004 yielded 154 tracks satisfying our criteria with a total duration of 785 h. Individual tracks range in length from the minimum allowed length of 2.5 to 55 km with durations from less than 1 h to nearly a day. A total of 44 full tracks and 29 partial tracks comprising 27% of the total track duration occurred during intervals when fin whale calls are detected off the track.

A. Call types

The tracks contain three call types: A 18 Hz down-swept pulse with a center frequency of 17 to 20 Hz, a narrow-band backbeat with a center frequency of 16 to 17 Hz, and a higher frequency 24-Hz down-swept pulse whose frequency can vary from 21 to 30 Hz. The 18 Hz pulse is the most common call type in this data set [Fig. 5(a)], comprising 81% of the calls and appearing in 98% of the tracks. Its rate of occurrence spikes from November to February and it is always associated with a backbeat. The 17 Hz backbeat call is the second most common call type comprising 10% of the calls and occurs primarily as the first call after a rest or a longer IPI. Backbeats are found on a large proportion of tracks with the 18 Hz down-swept pulse and are only found in association with this call. They do not form a separate peak in the frequency spectrogram [Fig. 5(e)] but can be identified in individual tracks based on their lower frequency and bandwidth. The 24 Hz pulse forms a separate peak in the call frequency histogram and is the least common, comprising 9% of the calls and occurring on 29% of the tracks. Three tracks are comprised entirely of the 24 Hz pulse. The rate of occurrence for the 24 Hz pulse remains approximately constant from September through March.

B. IPI categories

Based on the pattern of the IPI, the calling can be subdivided into 4 categories: (1) 25 s single IPI; (2) 24/30 s dual IPI; (3) 24/13 s dual IPI, and (4) irregular IPI. Most tracks fall into a single calling category but 13 tracks include intervals of 2 IPI categories and form a fifth category of tracks termed "mixed" IPI tracks. Table I summarizes the characteristics of the track types.

The 25 s single IPI tracks account for 16% of the total number of tracks and are characterized by calls spaced uniformly 25 s apart [Fig. 4(b)]. The IPI histogram for all of these tracks has a sharp peak centered at 24 to 25 s [Fig. 6(a)]. The frequency histogram [Fig. 5(a)] has a peak at 19 Hz with all the calls between 17 and 20 Hz. Backbeat calls occur in all of these tracks, most frequently on the trailing call of rests and on the occasional longer IPIs.

The 24/30 s dual IPI tracks are the most common and account for 48% of the tracks. The IPI histogram for all of these tracks [Fig. 6(b)] has a primary peak at 24 s and a secondary peak at 30 s. The overall ratio of the number of 24 to 30 s IPIs is ∼3.5 to 1 but it can vary markedly between tracks. The 30 s IPIs do not occur consecutively and for any track the number of 24 s IPIs before a 30 s IPI will typically vary from 1 to >10 with no regular pattern [Fig. 7(a)]. The frequency histogram [Fig. 5(b)] peaks at 18 Hz with all calls between 16 and 20 Hz. Backbeats occur on all of these tracks in about twice the proportion than for the 25 s single IPI tracks and are consistently the trailing calls of both rests and 30 s IPIs.

The 24/13 s dual IPI tracks account for 10% of the tracks. The IPI histogram for these tracks [Fig. 6(c)] has a primary peak at 24 s and a secondary peak at 13 s. The ratio of the number of 24 to 13 s IPIs is ∼1.5 to 1. On an individual track the 13 s IPIs are not distributed in a regular pattern but instead appear to be created by calls intermittently breaking a 25 s IPI sequence. These tracks can include all three call types. Backbeats are relatively rare and are primarily found as the trailing call of rests. Higher-frequency down-swept pulses with frequencies from 21 to 25 Hz [Fig. 7(b)] are found on 75% of the tracks and comprise 10% of the total calls. The 24 Hz calls tend to be found on the trailing edge of the shorter IPI [Fig. 7(b)] indicating that there is a tendency for the 13-s IPI to be created by a 24 Hz call interrupting an 18 Hz caller with a longer IPI rather than vice-versa.

The irregular IPI tracks account for 18% of the total and are characterized by a broad IPI distribution weighted toward smaller IPIs [Fig. 6(d)]. Individual irregular IPI tracks produce a range of IPI histograms, from a single peak near the 7 s limit imposed by our call detection algorithm, to multiple peaks all under 25 s. The frequency histogram [Fig. 5(d)] shows calls ranging from 16 to 30 Hz with peaks at 17, 19, and 24 Hz. This is the only track type to contain calls whose frequency exceeds 24 Hz [Fig. 7(c)]; 47% of the calls are categorized as 24 Hz calls (i.e., frequency ≥21 Hz). For

TABLE I. Characteristics of individual track categories and all tracks. Uncorrupted refers to the percentage of the total track duration that was not corrupted by calls from locations off the track. The call count is for the uncorrupted portions of the tracks. The percentages of 18 and 24 Hz pulses are derived from the uncorrupted portions of tracks based on the number of calls with frequencies ≤ 20 and ≥ 21 Hz, respectively. The percentage of backbeats was estimated from manual analysis of select track portions and subtracted from the percentage of 18 Hz pulses. Call type percentages were not calculated for the mixed IPI tracks and so the percentages in the All Tracks column are based on all tracks except the mixed IPI category. The mean length is the mean distance covered by the calling whale(s) and net length is the mean straight-line distance from the start to the end of each track. The meander parameter and criteria for classifying a track as transiting are described in Sec. II C. Tracks are assigned to 1, 2, or ≥ 3 frequency classifications based on the number of distinct peaks at or above 18 Hz in the call frequency histogram. Tracks to the north are the number of tracks in each category that have a northward component to their net distance traveled. $P_{binomial}$ is the one sided binomial probability that the north–south directionality of tracks is not southward for the 25 s single IPI, 24/30 s dual IPI, and 24/13 s dual IPI and not northward for the irregular IPI. Random walk distances and azimuths give the cumulative net length and direction obtained by putting tracks in each category end to end. $P_{random\ walk}$ is an estimate of the probability that randomly oriented tracks would travel at least as far as observed.

Parameter	25 s Single IPI	24/30 s dual IPI	24/13 s dual IPI	Irregular IPI	Mixed IPI	All tracks
Tracks	24	74	16	27	13	154
Total duration (h)	166	373	101	72	75	786
Uncorrupted (%)	31	66	64	70	91	73
Call count	5542	21 477	7395	5765	6843	47 022
Call type						
18 Hz pulse (%)	94	85	80	39	—	81
Backbeats (%)	6	15	10	9	—	10
24 Hz pulse (%)	0	0	10	52	—	9
Tracks						
Mean length (km)	18	19	21	13	21	18
Mean net length (km)	12	13	13	11	13	13
Mean duration (h)	6.9	5.0	6.3	2.7	5.7	5.1
Mean meander	1.7	1.8	2.0	1.2	2.4	1.8
Meander s.d.	1.3	2.7	1.9	0.3	2.2	2.1
Mean speed (km/h)	3.0	4.3	4.0	5.9	3.9	4.3
Speed s.d. (km/h)	1.7	2.0	1.8	2.5	1.5	2.1
Transiting (%)	17	36	38	60	31	37
Number of call frequencies						
1 frequency (%)	100	100	25	15	54	70
2 frequencies (%)	0	0	75	66	46	19
≥ 3 frequencies (%)	0	0	0	18	0	11
Swimming direction						
Tracks to the north	9	29	5	18	—	—
$P_{binomial}$	0.15	0.04	0.11	0.06	—	—
Random walk distance (km)	104	204	66	95	—	—
Random walk azimuth (°)	220	170	177	333	—	—
$P_{random\ walk}$	0.04	0.04	0.20	0.06	—	—

individual tracks, the frequency histogram has up to 5 peaks and has at least 2 peaks for 85% of these tracks. This is the only category to include tracks composed exclusively of "24 Hz" calls.

There are 13 mixed IPI whale tracks for which the locations indicate one continuous whale track but the calling characteristics switch, often several times, between 2 categories. For all but 3 of these the IPI switches between irregular IPI and either the 25 s single IPI or 24/30 s dual IPI. There are 2 tracks that switch from a 25 s single IPI to the 24/30 s dual IPI and 1 that switches from a 24/13 s dual IPI to a 25 s single IPI. Where the irregular and 24/13 s dual IPI portions of mixed IPI tracks contain multiple frequencies, the shift to a 25 s single and 24/30 s dual IPI coincides with the loss of the higher frequency calls.

Histograms of the rest spacing and duration for individual tracks show a wide variety of characteristics for each category. In some tracks rests are regularly spaced with similar duration while in others they vary. For the full data set the most frequent rest spacing is around 200 s but all spacings up to 700 s are common. Rest durations are also variable but most are <130 s and there are peaks in the histogram at 90 and 115 s.

C. Swimming characteristics

The estimated swimming speeds of individual tracks range from 1 to 12 km/h with a mean value of 4.3 km/h. The mean swimming speeds for the 24/30 and 24/13 s dual IPI tracks are very similar (4.2 ± 2.0 km/h, $n = 90$) but are different from the 25 s single and irregular IPI tracks (Table I). The swimming speeds for the 25 s single IPI tracks (3.0 ± 1.7 km/h, $n = 24$) are significantly slower (two sample t-test, $p = 0.004$) while those for the irregular IPI tracks (5.9 ± 2.5 km/h, $n = 27$) are significantly faster (two sample t-test, $p = 0.001$) (Rice, 1994).

The meander parameters vary from 1 to 8.5. The mean and standard deviation of the meander parameter (1.2 ± 0.3, $n = 27$) is lower for the irregular IPI tracks than for the 25 s single, 24/30 s dual, and 24/13 s dual IPI tracks combined

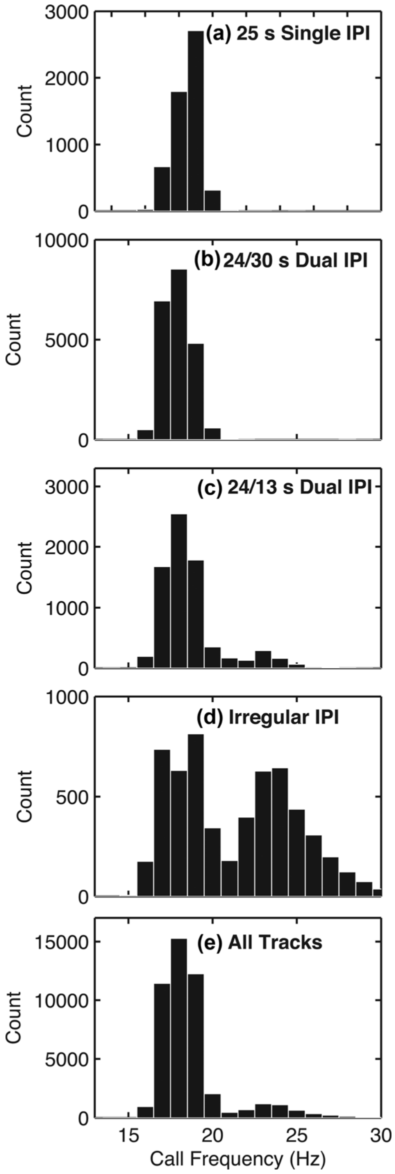

FIG. 5. Histogram showing the distribution of frequencies from portions of tracks that are not corrupted by off-track calling for (a) the 25 s single IPI tracks, (b) the 24/30 s dual IPI tracks, (c) the 24/13 s dual IPI tracks, (d) the irregular IPI tracks, and (e) all tracks.

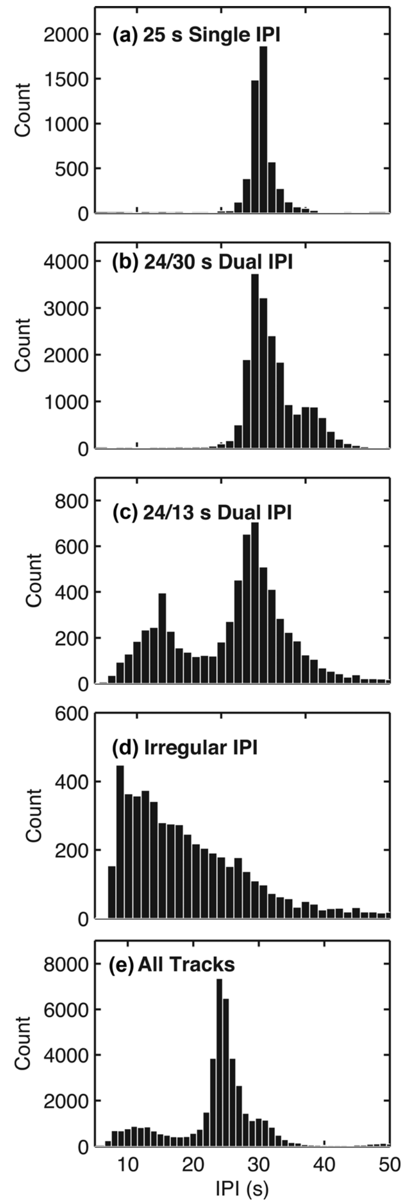

FIG. 6. Histograms showing the distribution of IPIs from portions of tracks that are not corrupted by off track calling for (a) the 25 s single IPI tracks, (b) 24/30 s dual IPI tracks, (c) the 24/13 s dual IPI tracks, (d) the irregular IPI tracks, and (e) all tracks.

(1.8 ± 2.4, $n = 114$). The smaller mean and standard deviation for the irregular IPI track meander parameters reflects the lack of irregular IPI tracks with high meander parameters. The tendency for the irregular IPI tracks to be faster and straighter is reflected in the relatively high percentage (60%) of those tracks that meet the requirement for a transiting track. Similarly, a small percentage (17%) of the 25 s single IPI tracks are transiting because they have slower swimming speeds.

Although 27% of the track duration is corrupted by off-track calls that are sufficiently loud to be detected by the spectral detection method, in most instances these calls are too far ($\gtrsim$15 km) from the network to be located. However, there are 5 periods totaling 8 h during which whales were calling concurrently on two tracks (Fig. 8). There are also another $\sim$11 h during which time calls were located off tracks in a consistent location but the number of locations, calling duration, and path lengths are too small to meet the criteria for a track. In all cases, concurrent tracks are always separated by >5 km and there is no indication that the whale movements are coordinated. Figure 8 shows one example; over a 4 h interval a 25/30 s dual IPI track located to the north of the network heads east while a second 25-s single IPI track to the west heads south.

D. Track distribution and directionality

The distributions of track types throughout the year and their directions show distinct patterns (Fig. 9). The irregular IPI tracks occur primarily from August to October and tend to be directed to the northwest [Fig. 9(a)]. The 25 s single IPI tracks are the dominant track type in November [Fig. 9(b)] and all but three occur between November and January. The 24/30 s dual IPI tracks start in November and continue

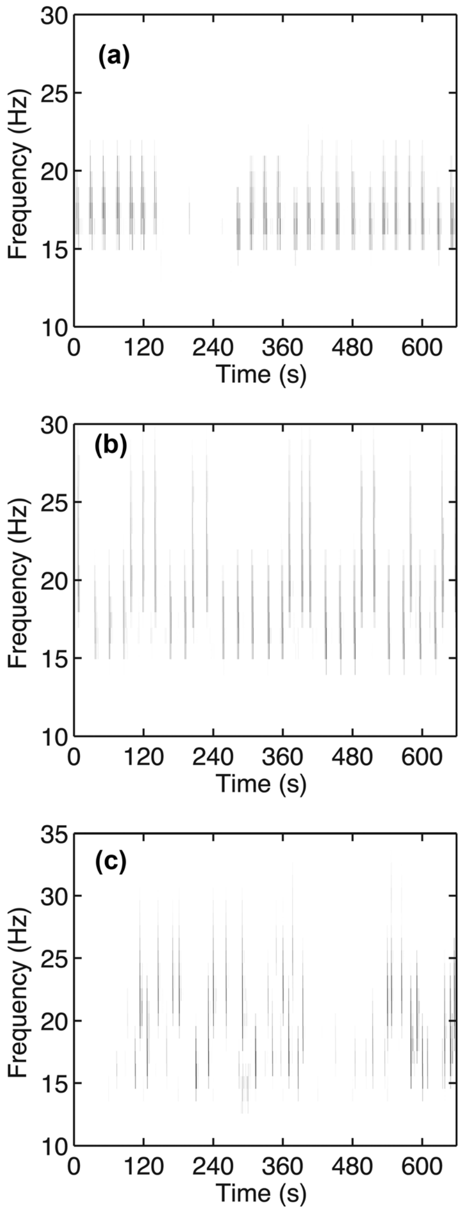

FIG. 7. Example modified spectrograms of 650 s of data for (a) a 24/30 s dual IPI on 4 February 2004 showing both a resting interval from ∼145 to 285 s and two longer IPIs starting at 360 and 480 s; (b) a 24/13 dual IPI on 14 January 2004 showing calls centered at two frequencies and the short IPI correlating with the change from the lower frequency call to the higher frequency call; and (c) an irregular IPI on 19 September 2003 showing short IPIs and several separate frequencies.

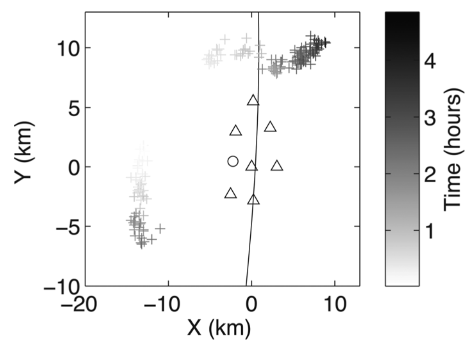

FIG. 8. Example of concurrent whale tracks from 10 November 2012 plotted with the same conventions as Fig. 6.

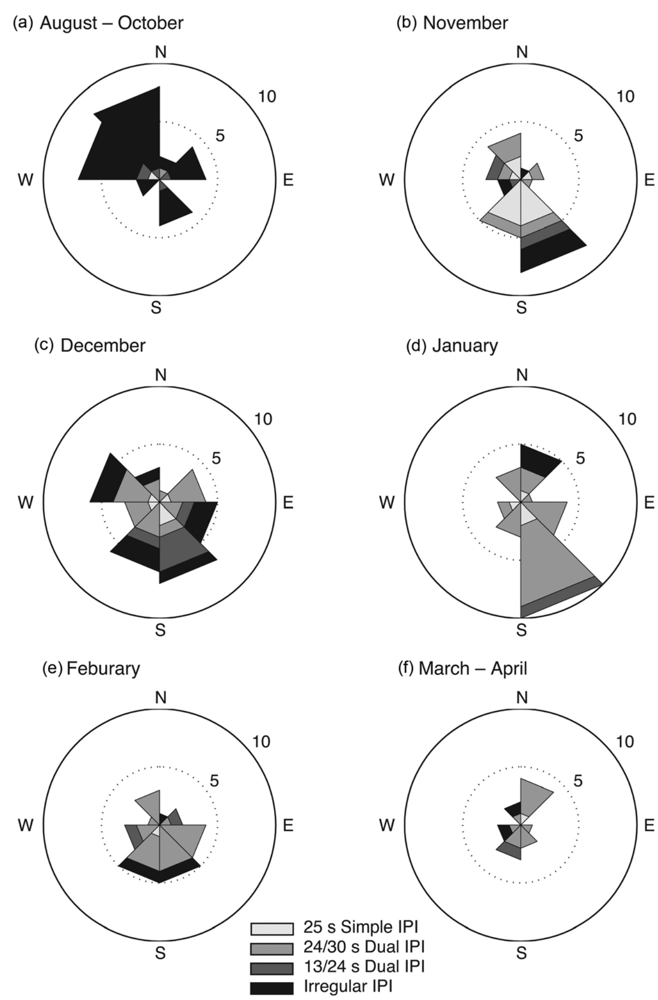

FIG. 9. Rose diagrams showing the temporal and directional distribution of whale tracks by category for (a) August through October, (b) November, (c) December, (d) January, (e) February, and (f) March and April. Mixed IPI tracks are excluded from the plots.

through April with the highest numbers from December to February [Figs. 9(c)–9(e)]. The 25 s single and 24/30 s dual IPI tracks have a tendency to be oriented southward and an overall directionality towards the south-southeast. The 24/13 s dual IPI tracks occur from September to March with the highest number in December [Fig. 9(c)]. They also tend to be southward.

Two statistical tests were conducted to test the significance of track directionality (Table I). First a one-sided binomial test (Rice, 1994) was applied to determine if the larger number of tracks headed either northwards or southwards might be expected in a random distribution. The northward directionality of the irregular IPI tracks is not quite significant at the 95% confidence level but when only the tracks in August to October are considered ($x = 16$, $n = 21$) it is significant ($p = 0.01$). The southward directionality is significant at the 95% confidence level for the 24/30 s dual IPI tracks but not for the 25 s single and 24/13 s dual IPI tracks, which may just reflect the smaller sample sizes. The probability of a random directionality for these three categories combined ($x = 43$, $n = 114$) is 0.03.

Second random walk tests (Rayleigh, 1919) were applied to each category by summing the cumulative displacement of tracks and determining if they are consistent with a random walk with step lengths equal to the average length of the individual tracks in the category. The results show that the 25 s single and 24/30 s dual IPI tracks are inconsistent with a random walk at the 95% significance level while the irregular IPI tracks just fail to meet this significance level (Table I). The 24/13 s IPI tracks cannot be distinguished from a random walk.

The spatial density of fin whale tracks around the network (Fig. 10) appears non-random. The highest densities of calling whales are observed within and to the east and north of the network while densities to the south and particularly the southeast are markedly lower. Overall the densities in the quadrant centered to the southwest are less than half those in the northeast quadrant. An inspection of similar plots for the different track categories suggests that the observed spatial patterns are a result of non-random distributions for the single and dual IPI track categories, rather than for the irregular IPI tracks that tend to transit across the region.

IV. DISCUSSION

In this study 154 whale tracks lasting for nearly 800 h were obtained over 1 yr from a small region in the Northeast Pacific Ocean. This work builds upon earlier studies with OBS data that localized a small number of fin whale calls to obtain tracks (McDonald *et al.*, 1995; Rebull *et al.*, 2006). The quality of each call sequence in this survey was verified by an analyst and is comparable to calling bouts observed during focal animal follows (Watkins, 1981; Watkins *et al.*, 1987). Although swimming speeds will be underestimated for meandering tracks because the location uncertainty for the tracking algorithm prohibits resolution of the small-scale non-linearity, the range of swimming speeds reported here (1 to 12 km/h) is consistent with previous observations. For example, aerial observations yield sustained near-surface swimming speeds from <1 km/h to 16 km/h (Watkins, 1981).

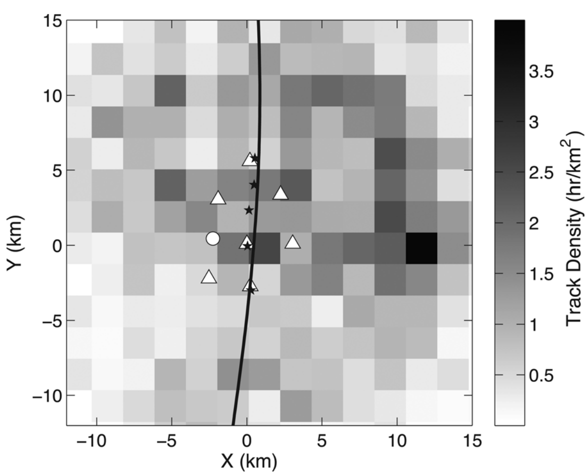

FIG. 10. Map showing the density of tracks on the rotated grid used for the locations (Fig. 1) in units of hours per square kilometer. The position of the ridge axis, OBSs, and vent fields are shown using the same convention as Fig. 1.

Given the global range of the fin whale's habitat (Watkins, 1981) and evidence that individuals cover large distances (Cotte *et al.*, 2009), it is likely that the 154 tracks represent many individuals. The tracks are thus complementary to those obtained by tagging, which are typically limited to a small number of individuals but either cover a longer duration (Cotte *et al.*, 2009) or provide more information such as dive profiles (Croll *et al.*, 2002; Croll *et al.*, 2001).

A. Calls types

The 18 Hz down-swept pulse and the 17 Hz backbeat are always found in association and together constitute over 90% of the calls. In a global compilation of song data backbeat calls are present in only 44% of fin whale songs (Hatch and Clark, 2004). In our study backbeats appear to be in a large proportion of tracks containing the 18 Hz pulse. Hatch and Clark (2004) also report that backbeats are preferentially incorporated into fin whale songs in the late summer and early fall (Hatch and Clark, 2004). This also contrasts with this study, where backbeats are most common from December through February when 24/30 s dual IPI tracks occur in large numbers and are the dominate track type.

A higher frequency down-swept pulse has been reported previously in the Northeast Pacific (McDonald *et al.*, 1995; MacDonald and Fox, 1999). McDonald and Fox (1999) note that it makes up >90% of the summer calling at high latitudes in the Northeast Pacific based on extensive unpublished data. This call, which is described as the "20 to 35 Hz irregular repetition interval," has been recorded near Hawaii, where it was attributed to fin whales (Thomson and Friedl, 1982; McDonald and Fox, 1999). However, more recently the same or a very similar call has been attributed to sei whales based on concurrent visual and acoustic observations near Hawaii (Rankin and Barlow, 2007)

In our data set the higher frequency "24 Hz" pulse constitutes about 9% of the calls and while its frequency varies, it is clearly distinguishable from the 18 Hz pulse since there are very few calls at 21 Hz [Fig. 5(e)]. Unlike the 18 Hz pulse which is found in all track categories, the 24 Hz pulse is only found in the 24/13 s and irregular IPI tracks. Since the 24 Hz pulse is found in association with the 18 Hz pulse in all but 3 of the 35 tracks where it is present, it would be surprising if it were from a different species. Since the 18 Hz pulse is associated with males in the breeding season (Croll *et al.*, 2002; Watkins, 1981; Watkins *et al.*, 1987), it might be inferred that the 24 Hz pulse does not come from mature males. If only males vocalize (Croll *et al.*, 2002), one possibility is that the higher frequency call is produced by smaller immature males.

B. IPI

The spacing of calls in fin whale songs has been shown to be an effective measure of population identity that may separate stocks or groups within the species (Hatch and Clark, 2004; Castellote *et al.*, 2011). Globally, calling bouts have IPIs ranging from 4 to 46 s with the most common intervals between 7 and 26 s (Watkins *et al.*, 1987; Hatch and Clark, 2004). Examples of the dominant IPIs in other regions include a 7/11 s doublet found near Cape Cod (Watkins, 1981), a 12 s IPI found in the waters near Bermuda (Watkins, 1981), and a 12 to 15 s in the Western Mediterranean Sea (Castellote *et al.*, 2011). In the Northeast Pacific, McDonald *et al.* (1995) reported a 19 s interval for data collected in 1990 and an IPI of ∼20 s can be deduced for many of the Northeast Pacific fin whales sampled by Hatch and Clark (2004) in 1995–1996 and 2000 (see Fig. 4 of that study). For our study the dominant IPI is 24 s. Since the study of McDonald *et al.* (1995) was conducted only about 300 km south of the Endeavour site, one possibility is that there has been a significant change in the IPI of Northeast Pacific fin whale on a decadal a timescale.

We interpret both the 25 s single IPI and the 24/30 s dual IPI as single whales. The single IPI is seen in data from surveys in many geographic locations other than the Northeast Pacific Ocean [Hatch and Clark (2004) Fig. 4; and Watkins *et al.* (1987)] and its seasonal occurrence has been linked to the breeding season. The 24/30 s dual IPI differs from the doublet call reported for the North Atlantic (Watkins, 1981) in that the two IPIs do not alternate but occur in a more complex pattern. This type of calling-pattern has not been discussed in the literature. Although there is overlap in their occurrence (Fig. 9), the 25 s single IPI is more prevalent in November while the 24/30 s dual IPI is the dominant song type from December through the end of the calling season. The simple IPI tracks are also characterized by slower swimming speeds and a smaller proportion of tracks that are not corrupted by off-track calling (Table I), suggesting that they occur when there are more calling whales in the vicinity.

We infer that the 25 s single IPI and the 24/30 s dual IPI are produced by the same population of whales. Some of the 25 s IPI tracks include a small number of larger IPIs that tend to be near 30 s IPI and the proportion of 30 s IPI varies between 24/30 s dual IPI tracks. There are two mixed IPI tracks in which the IPI appears to change in mid-track from the 25 s IPI to the 24/30 s dual IPI. In one track this happens abruptly following a rest in calling and so might be attributed to two whales being mistakenly assigned to the same track but in the other, the change in IPI pattern occurs without a break in calling.

Since 75% of the 24/13 s dual IPI call sequences include 24 Hz pulses in addition to 18 Hz pulses, they must either be attributed to a single whale vocalizing at two frequencies or to a pair of whales vocalizing at different frequencies. The latter interpretation seems more likely for three reasons. First, while fin whales can call at multiple frequencies up to 135 Hz (Watkins *et al.*, 1987), there are no previous reports of individual fin whales generating down-swept calls at two distinct frequencies near 20 Hz. In contrast, there are published examples of calling and counter calling (Watkins, 1981; McDonald *et al.*, 1995). Second, as noted above the 24 Hz pulse is nearly always observed as the trailing edge of the 13 s IPIs, which is consistent with the 24 Hz pulse being a counter call that interrupts this longer IPI. Third, on the one mixed IPI track that switched from the 24/13 s dual IPI to a 25 s single IPI, the change in the IPI category coincided with the loss of the 24 Hz pulse. This can be simply explained if a whale counter calling at 24 Hz stopped calling, leaving a single whale vocalizing at 18 Hz.

If the 24/13 s dual IPI whale tracks are generated by two callers it raises interesting behavioral questions. The track characteristics including dominant IPI, speed, tortuosity, seasonal occurrence, and directionality are similar to the 25 s single and 24/30 s dual IPI tracks that are attributed to the breeding display of a single male. If only male fin whales sing (Croll *et al.*, 2002; Watkins *et al.*, 1987), what would motivate two males to travel together calling and responding? If the 24 Hz pulse is attributed to a smaller immature whale then it can be inferred that the second whale in these tracks is sometimes a mature male and sometimes an immature whale. Since the frequency of the 24 Hz pulses in the 24/13 s dual IPI tracks [Fig. 5(c)] are at the lower end of the 21 to 30 Hz range for these calls observed in the full data set [Fig. 5(e)], these calls might be interpreted as from a whale nearing maturity if the call frequency is an indication of size.

The irregular IPI tracks are most easily interpreted as multiple whales singing and/or responding as they swim together. The peak IPI in the histogram is at 8 s [Fig. 6(d)], which is close to the minimum separation allowed for two events in the detection algorithm to avoid triggering on multiples. Inspection of the data shows that some irregular IPI tracks can have very closely spaced calls. All but 2 of the 27 irregular IPI tracks include 24 Hz pulses and the frequency histograms for individual tracks contain up to 5 distinct center frequencies (Table I). Irregular IPI patterns with multiple frequencies are visible in several published spectrograms from the Northeast Pacific (Charif *et al.*, 2002; McDonald and Fox, 1999; McDonald *et al.*, 1995; Moore *et al.*, 1998), although in some instances the number and relative position of whales is unknown. McDonald *et al.* (1995) used tracking to infer that an irregular IPI sequence comprised three whales calling at distinct frequencies and swimming in the same direction a few kilometers apart. McDonald and Fox (1999) infer four calling whales based on call frequency content and bearing.

In this study, the different frequency calls in the irregular IPI tracks are not resolved onto separate tracks. Given the location uncertainties, this indicates that the callers are swimming no more than one to several kilometers apart from each other. The high proportion of higher-frequency calls with mean frequencies up to 30 Hz [Fig. 5(d)] suggests that irregular IPI tracks include many callers that are not mature males. The faster swimming speed and consistently low meander parameters of these tracks are consistent with groups of whales communicating while transiting through the experiment area.

There are 10 tracks where either 25 s single or 24/30 s dual IPI calling patterns switch back and forth to irregular IPI. The simple explanation is that the single whale being tracked is either joined by or was always in the company of other whales that start or stop vocalizing. The presence of irregular IPI in mixed IPI tracks implies that the 18 Hz pulses in the irregular IPI are not generated by a completely distinct subset of 18 Hz callers from those in the other track types.

C. Seasonality and directionality of tracks

Fin whale calling is strongly seasonal in our data set with all the tracks between August and April and the highest numbers from November to February. These seasonal variations do not require variations in the number of fin whales present in the study area because they can be explained by seasonal changes in sound production (Watkins *et al.*, 2000). In high latitude areas there are many observations of relatively silent fin whales during summer months (Stafford *et al.*, 2007; Simon *et al.*, 2010). Fin whale calling rates have been previously observed in acoustic surveys of the Northeast Pacific Ocean to be highest during the winter months (Stafford *et al.*, 2007; Watkins *et al.*, 2000; Simon *et al.*, 2010), which is consistent with gestation estimates that indicate mating in this season (Watkins *et al.*, 1987). This fits the well accepted theory that a stereotyped song is a male breeding display (Croll *et al.*, 2002; Watkins, 1981; Watkins *et al.*, 1987).

Our data documents a systematic progression in the dominant IPI from irregular IPI in August–October to 25 s single IPI in November to 24/30 s dual IPI throughout the winter months (Fig. 9) that indicates changes in social behavior. We interpret the irregular IPI as a social calling pattern indicative of multiple whales traveling together (Payne and Webb, 1971). As winter progresses and the onset of the mating period commences (Watkins *et al.*, 1987), the track class shifts to the solitary 25 s single IPI and the 24/30 s dual IPI.

Acoustic monitoring in other studies has shown migratory movements of one whale population between two locations by comparing inter-note intervals recorded in both locations (Castellote *et al.*, 2011). This study is limited to one location but constrains the travel direction and variations in IPI and group size that occur over the year. The progression shown from August through April in both classes of tracks detected and the net directionality from northward in the fall to southward in the winter (Fig. 9) seems to conflict partially with the conclusions from studies of both whaling data and tagged whales (Mizroch *et al.*, 1984; Mizroch *et al.*, 2009) that recorded systematic movement between low latitude winter grounds and high latitude summer grounds. The northward irregular IPI tracks in the fall with many 24 Hz callers may indicate that a portion of the population, possibly including immature males, does not migrate south in the fall. The southward movement of the other categories in the winter is not necessarily incompatible with a conventional migration pattern but would require that these callers swim silently northward as soon as the calling tapers down in March and April.

D. Spatial distribution of fin whales

Because our location algorithm is not designed to separate overlapping calls, the observation of 5 pairs of concurrent tracks totaling 8 h as well as 11 more hours when there are short intervals of calling located off-track may tend to under-report the time when there are 2 separate whales or groups of whales vocalizing in the vicinity of the network. Nevertheless it appears that these tracks are relatively rare. There are 654 h of tracks from November through February, which gives an expected number of trackable whales at any given time of 0.23. Assuming that these tracks occur randomly in time, the Poisson's distribution (Rice, 1994) predicts that two or more should be present for over 60 h. Because concurrent tracks are much less frequent and are always well separated, our data supports previous studies that report calling whales or groups of whales to be separate from one another (Watkins, 1981).

One hypothesis that motivated this study was that fin whales might be found preferentially near the ridge axis to exploit the increased zooplankton biomass (Burd *et al.*, 1992; Thomson *et al.*, 1992; Burd and Thomson, 1994, 1995). The track density plot (Fig. 10) shows a non-random distribution of tracks with more tracks near the network and to the north and east. Variations in network aperture might lead to different sensitivity to the north and south than to the east and west. The presence of thick sediments to the east may impact the relative sensitivity to the east and west of the ridge axis because of the effects of the bottom lithology and roughness on seafloor multiples. However, it is difficult to attribute all spatial variations to sensitivity effects. For example, the density of the calls to the northeast of the network is nearly twice that to the southeast despite similar network geometry and seafloor characteristics. The mean near surface currents in the region are characterized by flow to the east and northeast associated with the Eastward North Pacific Current (Strub and James, 2002). The higher density of tracks seen within the network and to the north and east is thus not inconsistent with a source of food near the rise axis that is advected by the ocean currents. High densities of zooplankton biomass have been shown to co-occur with cetaceans in many studies (Cotte *et al.*, 2009; Stafford *et al.*, 2007), and while there is not an established link between vocal behavior and feeding behavior, singing males have been observed in areas of high food concentration (Croll *et al.*, 2002) and singing whales are generally found near non vocalizing whales (Watkins *et al.*, 1987). A more definite test of the linkage between hydrothermally-supported zooplankton and fin whales would require measurements of zooplankton concentration in the winter and a better understanding of the linkages between vocalizing whales and whales feeding in the vicinity.

V. CONCLUSIONS

In this study the acoustic behavior of fin whales has been linked to their tracks over 1 yr in a small portion of the Northeast Pacific Ocean. These results demonstrate the usefulness of seafloor seismic networks in studying fin whales. OBS networks can provide long-term opportunistic monitoring capabilities that would be expensive to duplicate in a dedicated experiment. The primary conclusions of this study are:

(1) The 18 and 24 Hz pulses are distinct call types that are likely indicative of different individuals.
(2) The dominant IPI for the Northeast Pacific fin whale is 24 s.
(3) The 25 s single IPI and the 24/30 s dual IPI are probably single whales generating 18 Hz pulses.
(4) The 24/13 s dual IPI is a previously unidentified type of track that is possibly indicative of two calling whales traveling together, one of which may use a 24 Hz pulse.

(5) The irregular IPI is indicative of multi-whale groups that contain a high proportion of 24 Hz pulses.
(6) The swimming patterns show northward movement of groups of transiting whales from August to October and a southward movement from November to April of 25 s single, 24/30 s dual, and 24/13 s dual IPI tracks.
(7) The call density shows a non-random spatial distribution that is not inconsistent with a source of enhanced concentration of zooplankton above the hydrothermal vent fields.

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