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14. ABSTRACT
Long-term monitoring of underwater sounds using U. S. Navy SOSUS and other hydrophone arrays allowed us to follow the seasonal distribution of underwater calls produced by blue, fin and humpback whales across the North Pacific. These new data from this current study have been added to data of previous 7 years' deep-water monitoring,enabling us to document year-to-year variations in marine mammal calling. These data have also been added to the marine mammal sound archive at the Woods Hole Oceanographic Institution. Tracking of individual whales has has been accomplished using the Navy's deep-water monitoring system as evidenced by the tracking of a unique 52-Hz call, with his current study cumulating a 12 year track The large WHOI sound database provided comparisons and analysis of these sounds. The year-round monitoring of blue whales has uncovered at least two distinct call types which occur in very specific regions in the North Pacific. These data collected across a broad area without the restriction of weather or time of day are invaluable to researchers interested in population trends of marine animals.

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FINAL REPORT

GRANT #: N00014-03-1-0734

PRINCIPAL INVESTIGATOR: Dr. William A. Watkins

INSTITUTION: Woods Hole Oceanographic Institution

GRANT TITLE: Marine Animal Sound Database

AWARD PERIOD: 1 May 2003 - 30 April 2004

OBJECTIVE: To follow the seasonal distribution of underwater calls from blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*) and humpback (*Megaptera novaeangliae*) across the North Pacific Ocean. These and other underwater animal sounds are organized in the WHOI 50-year archive allowing sound comparisons and study, and development of passive acoustic tracking.

APPROACH: Underwater sounds are monitored using U.S. Navy SOSUS and other hydrophone arrays in order to record the calls from these species as they occur in the deep water across the North Pacific. The acoustic data are analyzed on site at NOPF, Whidbey Is., WA, by ex-Navy personnel experienced both in recognition of the whale sounds, as well as in operation of these Navy acoustic systems. The call data are archived by the Woods Hole Oceanographic Institution (WHOI) and the characteristic patterns of call occurrence are analyzed. Long-term monitoring has allowed measures of the changes in geographic distribution of calling whales across these waters, and permitted correlation with changes imposed by environmental climate and natural biological cycles of these populations. Tracking of individuals by means of the arrays such as those of the Navy SOSUS allowed year-round observations and accurate well-tested locations. Tracks of the unique 52-Hz whale demonstrated the detail possible in following the activities of these deep water populations.

ACCOMPLISHMENTS: Year-round monitoring of whale sounds across the North Pacific was continued for a seventh year. Whale seasonal distribution was defined for local areas in four Regions (NW, NC, NE, and SE) along the continental margins. Call types defined apparently distinct whale populations in the different regions. The unique 52-Hz whale was tracked for the 12 year, tracks varied from 700 to more than 11,000 km in distance as the whale moved at speeds of less than 4 km/hr. The large WHOI archive of marine animal underwater sounds provided comparisons and analysis.

CONCLUSIONS: Blue whales are heard calling year-round, particularly in the NW Region with peak calling in early fall. There appears to be two blue whale populations with distinct call types, one dominant in the NW and NC Regions, the A call type, and a second dominant in the NE and SE Regions, the A-B call type, with both call types occurring in the NC, NE and SE Regions. Calling in blue whales was affected by environmental variations.
Fin whale calling peaked in winter, with nearly no calls in summer. In contrast to blue whales, calling fin whales were most numerous in particular areas of the NC, NE and SE Regions, with very few in the NW. Calling by fin whales did not appear to be affected by environmental variations.
Humpback singing in these monitored Regions has been variable. Singing often started in December in the NC Region, moved to the SE Region from January to March, and ended back in the NC Region in April. Singing by humpback whales did not appear to be affected by environmental variations.

SIGNIFICANCE: Significant blue whale calling data has been provided by this study. The previously seldom encountered A call type is evidently the dominant blue whale call heard in these deep waters of the North Pacific. The A-B call was only dominant in the NE Region which is the most often visually surveyed region in the North Pacific.
The WHOI sound archive of marine animal sounds, now stored in digital format, has provided the data for comparisons, analyses and tracking of the acoustic behaviors of these deep water whales.

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Twelve years of tracking 52-Hz whale calls from a unique source in the North Pacific

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Abstract

A unique whale call with 50–52 Hz emphasis from a single source has been tracked over 12 years in the central and eastern North Pacific. These calls, referred to as 52-Hz calls, were monitored and analyzed from acoustic data recorded by hydrophones of the US Navy Sound Surveillance System (SOSUS) and other arrays. The calls were noticed first in 1989, and have been detected and tracked since 1992. No other calls with similar characteristics have been identified in the acoustic data from any hydrophone system in the North Pacific basin. Only one series of these 52-Hz calls has been recorded at a time, with no call overlap, suggesting that a single whale produced the calls. The calls were recorded from August to February with most in December and January. The species producing these calls is unknown. The tracks of the 52-Hz whale were different each year, and varied in length from 708 to 11,062 km with travel speeds ranging from 0.7 to 3.8 km/h. Tracks included (A) meandering over short ranges, (B) predominantly west-to-east movement, and (C) mostly north-to-south travel. These tracks consistently appeared to be unrelated to the presence or movement of other whale species (blue, fin and humpback) monitored year-round with the same hydrophones.

Keywords: Acoustic tracking; 52-Hz whale calls; Underwater sounds; Whale tracking

1. Introduction

Biological sounds with emphasis near 50–52 Hz were recorded over the last fifteen years from a single source in the deep waters across the North Pacific basin. These calls, referred to here as 52-Hz calls, were identified during systematic monitoring of whale sounds from US Navy Sound Surveillance System (SOSUS) and other hydrophone arrays (Watkins et al., 2000a, b, 2001). Studies of the occurrence of calling whales in these waters were conducted by the Navy beginning in the late 1980s, and a systematic monitoring program by the Woods Hole Oceanographic Institution (WHOI) has continued since 1995. The 52-Hz calls were initially reported by Watkins et al.

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(2000b), and were assumed to be produced by a whale because of their somewhat similar characteristics to known sounds from baleen whales. These 52-Hz calls also have been noted on geophysical hydrophones in the Gulf of Alaska by NOAA Pacific Marine Environmental Laboratory's Vents Program (2003) with sample calls displayed on the Web. The calls have been consistently distinctive and readily identifiable, and their source has been tracked seasonally during the last 12 years.

Low-frequency underwater sounds from individual whales have been recorded and tracked since the 1950s by means of US Navy SOSUS and other hydrophone installations in the North Atlantic (cf. Walker, 1963; Schevill et al., 1964; Patterson and Hamilton, 1964; Watkins, 1981; Watkins et al., 1987) and in the North Pacific (cf. Kibblewhite et al., 1967; Northrop et al., 1968; Thompson and Friedl, 1982). SOSUS provided convenient, accurate, and well-tested acoustic tracking, although over the next 40 years, such classified Navy data usually were not available for biological study. Then in 1992, data from US Navy Integrated Sound Surveillance Systems including SOSUS were partially declassified, allowing new, spectacular observations of calling whales in deep water, such as the 43-day, 3200-km track of a lone calling blue whale in the western Atlantic (Clark, 1995).

Much of the earliest tracking of whale sounds was from moored hydrophone systems, and was focused on the low-frequency sounds from fin whales (Walker, 1963; Schevill et al., 1964; Northrop et al., 1968). Tracking of the movements of other baleen whales in similar ways waited another 20–30 years, for example, bowhead whales (Clark and Johnson, 1984; Clark, 1989) and blue whales (Edds, 1982; McDonald et al., 1995; Moore et al., 2002). Shipboard hydrophone systems and sonobuoys also were used to track calling baleen whales (Watkins and Schevill, 1972; Watkins, 1981; Clark and Fristrup, 1997; McDonald et al., 2001), but because of low-frequency ship and wave noise, this has been less useful than passive moored systems for longer-term tracking of low-frequency calls. Coherent tracks longer than a few hours or days have been rare.

The distinctiveness of the 52-Hz calls has allowed unusually long-term, confident tracking. Analysis of these calls and their variations compared to the sounds of other whales will be the subject of another report. Here, we describe the seasonal movements of the 52-Hz whale over twelve successive years.

2. Methods

The 52-Hz calls were recorded by hydrophones of the US Navy SOSUS and other arrays during monitoring to quantify the distribution and seasonal occurrence of calling whales across the North Pacific (Watkins et al., 2000a, b). The acoustic data from 10 or more of these arrays were monitored regularly by analysts experienced in operation of the Navy signal processing systems and trained in recognition of the sounds produced by the different whale species.

The 52-Hz calls were easily distinguished from sounds produced by the whale species regularly monitored in detail in these same waters, particularly blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*), and humpback whales (*Megaptera novaeangliae*). The 52-Hz tracks were compared with locations and tracks for these whales monitored in the same waters during the same period by the same equipment (Watkins et al., 2000a, b, 2001; Moore et al., 2002).

For the 52-Hz call tracking, systems at the US Naval Ocean Processing Facility (NOPF), Whidbey Is., WA, were used without modification for monitoring, acoustic source location, and signal processing. These Navy facilities, hydrophone arrays, their characteristics, and associated data processing techniques have remained classified. For source location, call sequences from multiple arrays of hydrophones were analyzed and matched in detail spectrographically. Call series that could be exactly matched on three to five or more arrays accounted for 70% of the source locations. Acoustic positions were derived by triangulation of beam-formed sound directional vectors from the arrays, and refined by differences in sound arrival-time measurements between receiving elements. Locations for the source of repeated groups of calls provided consistent replication of positions. Source position accuracies were estimated to be within 1–10 km, frequencies were specified to 0.25 Hz, and time to 1 s. Analysis of the 52-Hz calls in Fig. 1 used a Kay Sonograph (C7029A, Kay Elemetrics, Pinebrook, NJ).

Detailed tracking of the 52-Hz source used Navy data prior to 1995, and since then, WHOI used averaged source positions from repeated call sequences within the previous 24 h, often from long bouts of successive call series. Distances and speeds were measured between each incremental track position, including track positions before and after gaps in calling during the same season. Tracking was continued across the gaps in calling (described below) because of the consistency of source speed, direction, and distance of travel, as well as the similarity and uniqueness of calls before and after these periods. For calculated track speeds and distance within any one season, it was assumed that the same source was being tracked when calling resumed. Likewise, similar calls from a unique source that occurred in successive seasons in the same regions of the North Pacific were assumed to be from the same individual.

The 52-Hz calling is described with specific terms. "Calls" denote individual, discrete tones of a few seconds duration that formed the basic unit of seasonal calling. "Groups" refer to clusters of 2–20 or more calls with up to 30 s between calls that constituted the usual calling sequence. "Series" indicate multiple call groups separated by up to 10 min. "Bouts" describe extended periods of calling sometimes over many hours with successive series of call groups. "Calling periods" refer to the time in which successive bouts of calling continued, varying from days to months with relatively consistent calling. "Gaps" in calling indicate variable periods, sometimes of several days, without calls during seasonal call tracking.

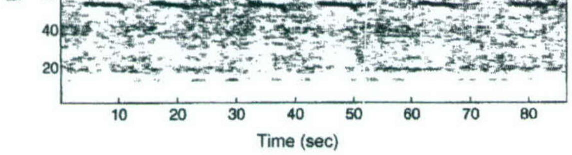

Fig. 1. Spectrogram of a group of 52-Hz whale calls from 3 February 1993, the second group of Fig. 2 and group B of Table 1.

3. Results

Distinctive tonal calls with emphasis at 52-Hz were detected in 1989, and for the next three years, these calls were received for a few weeks annually from a single source that remained generally in waters near 46°N 126°W. Although the deep waters of the North Pacific basin were monitored year-round via SOSUS and other hydrophone arrays, these calls have been the only ones found with similar characteristics. The 52-Hz calls have only been detected in north-central and north-eastern Pacific waters, and because they were consistently so different, a special effort was made to locate and monitor the source. These calls have been recorded seasonally now for 15 years, and their source has been tracked for 12. The calls were attributed to a whale because they had features that were typical of some of the repetitive low-frequency tonal sounds produced by baleen whale species (cf., Watkins and Wartzok, 1985; Watkins et al., 1992; Stafford, 2003; Stafford et al., 2001; Clark and Ellison, 2004).

The 52-Hz whale calls were characterized by (1) high received levels, characteristically well recorded on multiple arrays, (2) dominant frequencies of 50–52 Hz with sidebands of approximately 17 Hz, but with no energy at the fundamental frequency, (3) tones of 3–10 s centered on the dominant frequency, (4) downward sweeping tone frequencies of as much as 2 Hz, depending on duration, (5) grouped call sequences in repetitive series, and (6) reception from only one source.

The 52-Hz whale calls were unique. A typical group of these calls is illustrated in Fig. 1, with calls at 51.75 Hz, measured at the midpoint of the duration of the call. Sidebands were recorded at 69.25 and 34.5 Hz, but there was no fundamental frequency at the sideband interval. Typically, there was a variable mix of short (3–5 s) and long (6–10 s) calls, with each one centered on the dominant frequency. Intervals between calls in a group varied from 3 to 30 s.

Call groups also were clustered in series of 2–20 or more, with intervals between groups in series varying from 2 to 10 min (Fig. 2, Table 1). Series of call groups lasted variably from about 30 min to several hours. Such bouts of calling usually included many series of call groups. Calling periods contained many bouts of calling and lasted variably over a few hours to many days. Calling occurred on (87%) 55 of the 63-day calling period during the 92–93 track, illustrated by the total duration of calling each day (Fig. 3). There was no consistent pattern to the temporal succession of calls in groups, to the temporal pattern of the sequence of call groups within series, to the occurrence of calling during bouts, or in the amount or timing of calls during calling periods. Calling amounts during each successive track were different.

The 52-Hz tonal calls have been variable with short-term changes within groups and over longer time periods. These variations included lowered frequency components of particular calls and slower, as well as, more rapidly changing frequencies particularly at the end of calls. In addition, there has been a long-term gradual downward change in the dominant call frequency, so that after 15 years, the center frequency of the calls has become close to 50 Hz. In spite of such variation, these calls have remained consistently recognizable, never overlapping, well defined and distinct from other ambient sounds.

Gaps in calling of 1–16 days occurred irregularly during seasonal calling periods. There also were occasional longer gaps of 33–78 days toward the beginning of four of the seasons (93–94, 95–96, 01–02, and 03–04), as well as a gap of 42 days in the middle of the 97–98 season. During each of these gaps in calling, the whale's speed and direction of travel was maintained, and when calls resumed, they were like those that occurred before the gap. No other similar calls were recorded during these gaps in calling, leading us to conclude that when calling resumed, it was the same whale producing these unique calls. The 52-Hz calls were recorded during an average of 52% of the days during calling periods, ranging from 17% (93–94) to 87% and 86% (92–93 and 00–01) in different seasons.

The 52-Hz calls typically started and stopped abruptly, with no gradual increase or decrease in levels. These calls occupied a frequency band that often had relatively low-noise, and they were composed of distinctive call spectra that made them readily recognizable. The 52-Hz calls were consistently recorded well on multiple hydrophone systems, allowing confident tracking.

3.1. Tracking

The 12 seasonal tracks of the 52-Hz whale averaged 47 km/day, ranging from 31 to 69 km/day. Tracks lasted variably from 2 to 5 months, and each traversed different waters. Tracks varied in length from the 92–93 track of 708 km to the 02–03 track of 11,062 km, with an average track length of 5518 km. Tracks began variably between August and December (3 in August, 4 in September, 3 in October, and 2 in December), but all tracks ended within a period of a few weeks in January or early February (9 in January, 3 in early February). The tracks of the 52-Hz whale

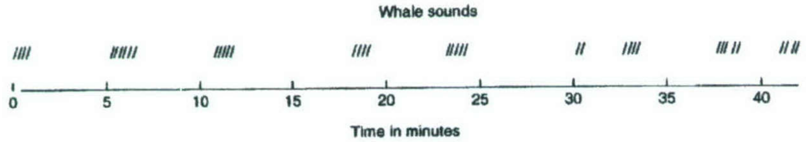

Fig. 2. Temporal sequence for a series of 52-Hz call groups from 3 February 1993. The group of Fig. 1 is the second one here.

Table 1
Times, durations, and intervals for calls and call groups portrayed in Fig. 2, with each group identified in sequence by letter and calls within groups by number (example, C4 is the fourth call in the third group)

Group/call	Time from start (min)	Call duration (s)	Time between calls (s)	Time between groups (min)
A1	0:01	7	9	
A2	0:17	6	7	
A3	0:30	5	9	
A4	0:44	5		4:23
B1	5:12	6	6	
B2	5:24	5	11	
B3	5:40	6	6	
B4	5:52	5	12	
B5	6:09	6	11	
B6	6:26	5		4:19
C1	10:50	6	6	
C2	11:02	5	8	
C3	11:15	5	6	
C4	11:26	5	9	
C5	11:40	5		6:29
D1	18:14	7	8	
D2	18:29	6	9	
D3	18:44	6	10	
D4	19:00	5		4:10
E1	23:15	6	6	
E2	23:27	5	11	
E3	23:43	6	9	
E4	23:58	6	9	
E5	24:13	5		5:56
F1	30:14	7	7	
F2	30:28	5		2:13
G1	32:46	7	9	
G2	33:02	6	7	
G3	33:15	5	8	
G4	33:28	5		4:10
H1	37:43	6	6	
H2	37:55	5	5	
H3	38:06	5	22	
H4	38:33	6	7	
H5	38:46	5		2:15
I1	41:06	7	7	
I2	41:20	6	17	
I3	41:43	6	6	
I4	41:55	5		

consistently were not related to the locations or movements noted for other calling whale species (blue, fin, and humpback) monitored closely year-round in these same waters (cf., Watkins et al., 2000b; Moore et al., 2002).

The first 2 tracks of the 52-Hz whale were less consistent than the succeeding ones. The beginning 92–93 track of 47 days was only 708 km. After 10 days of calling in the same general area that it had occupied for the previous three seasons, tracking began when the whale started to move. The whale stopped moving after 47 days, but continued to call for the last 6 days of its 63-day calling period. For all other calling periods during subsequent years, tracking was initiated with the first identified call of this whale and continued until calling stopped. The second 93–94 track was much longer but was less coherent with intermittent calling interspersed by long gaps in calling. Tracks in succeeding seasons were more consistent.

The 52-Hz whale tracks varied widely each season. To illustrate some general similarities among particular tracks, they have been divided arbitrarily into three categories (Table 2). The meandering tracks (**A**) were over short ranges (tracks 92–93, 96–97 and 00–01, Fig. 4). The west-to-east tracks (**B**) had predominantly latitudinal movements (tracks 93–94, 95–96, and 99–00, Fig. 5). The north-to-south tracks (**C**) had mostly long longitudinal travel (tracks 94–95, 97–98, 98–99, 01–02, 03–04, and track 02–03 had both **A** and **C** movement, Fig. 6). The 12 tracks fell into this category sequence: A, B, C, B, A, C, C, B, A, C, A/C, C (Tables 2 and 3). The long 02–03 track of 11,062 km was divided with the first half meandering (A) for 5849 km and the last half N–S (C) for 5213 km.

There was an overall, though variable, trend toward more consistency in the form, speeds and distances of the 52-Hz whale tracks with successive seasons. Of the first 5, 4 tracks had meandering and W–E characteristics with little southerly movement. Of the 12 tracks, 6 had N–S travel, including the last 3, and 5 of the last 7 (Fig. 6). The 4 meandering tracks (including first-half of 02–03) averaged 4218 km, the 3 W–E tracks averaged 4655 km, and the 6 N–S tracks (including last of 02–03) averaged 5897 km.

The tracks for the 52-Hz whale indicated relatively slow, continuous movement. Speed for all the tracks averaged 2.8 km/h (range 0.7–3.8 km/h). Meandering

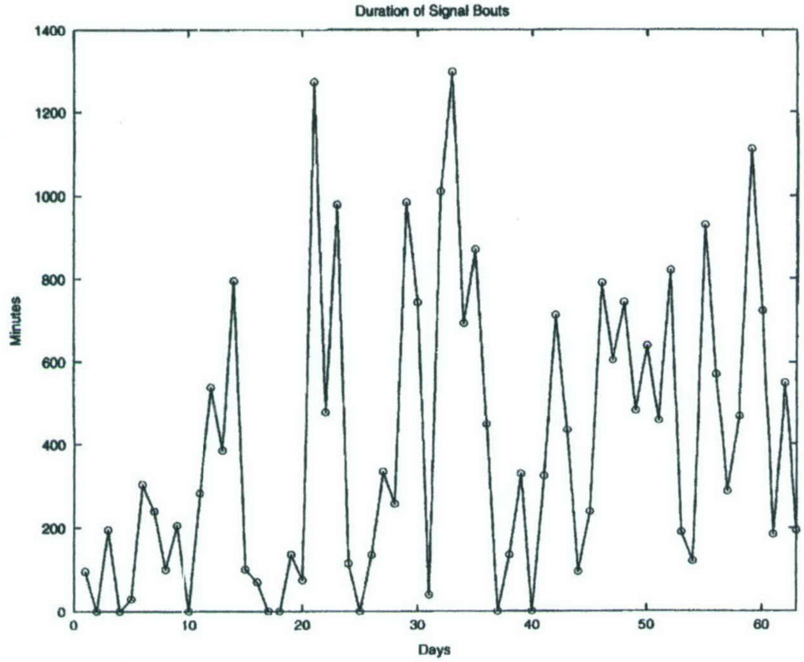

Fig. 3. Duration of daily calling during the 63-day calling period of 92–93.

tracks averaged 1.9 km/h, W–E tracks averaged 2.5 km/h, and the N–S tracks were fastest, averaging 3.5 km/h (range 2.9–3.8). The 12 tracks are plotted in Figs. 4–6, divided by the three categories: meandering, W–E, and N–S. Details of each track are in the Appendix. Track speeds and daily distances are listed in Table 2, and for each track, start and end times are given with positions and percent of calling days in Table 3.

3.2. Habitat

The 52-Hz whale roamed widely across the deep waters of the central and eastern portion of the North Pacific basin. Most of the tracks of this whale originated in northern waters (8 above 50°N, 1 below 45°N) and variably between 125W and 160W. As the tracks progressed, the whale generally moved slowly toward the east, then often turned a bit north and then south. The whale tracks remained mostly north of 50°N except for those with long north-to-south components which ended between 46°N and 22°N (Table 3, Figs. 4–6). Even during the meandering (A) tracks, the whale did not concentrate its activity in any particular locale. There were no apparent repeated patterns to the whale's travel.

The whale spent relatively little time in any particular area, and did not repeatedly visit the same location during any season, or in subsequent seasons except during passages on somewhat different tracks. The total amount of time spent in the different areas by the 52-Hz whale as it traversed these central and eastern waters of the North Pacific waters is plotted in Fig. 7. For this, the number of hours spent in each area during the whale tracks were added for each of the three track categories (A, B, C), and then the categories were plotted separately within successive blocks of approximately 550 × 550 km (between 10° east–west at these northern Latitudes and 5° north–south). This illustrates the generally random character of the whale movements, as well as the waters that were visited most. The area from 50°N to 55°N and 145°W to 155°W was traversed during tracks of all three categories, and was the area

Table 2
The 52-Hz track form, duration, total km distance, days heard calling, km/h speed, and average km distance per day traveled each season

YEAR	Form	Days	Distance	Call days	km/h	km/day
92–93	Meander	47	708	55/63	0.7	15
93–94	W–E	127	4891	21	2.5	39
94–95	N–S	56	3868	26	3.8	69
95–96	W–E	101	3160	19	2.6	31
96–97	Meander	78	4295	26	3.0	55
97–98	N–S	136	8447	41	3.5	62
98–99	N–S	113	4770	55	2.9	42
99–00	W–E	135	5916	97	2.5	44
00–01	Meander	132	6019	114	2.0	46
01–02	N–S	144	7293	74	3.5	51
02–03	Meander/N–S	176	11,062	129	3.2	63
03–04	N–S	106	5789	59	3.8	53

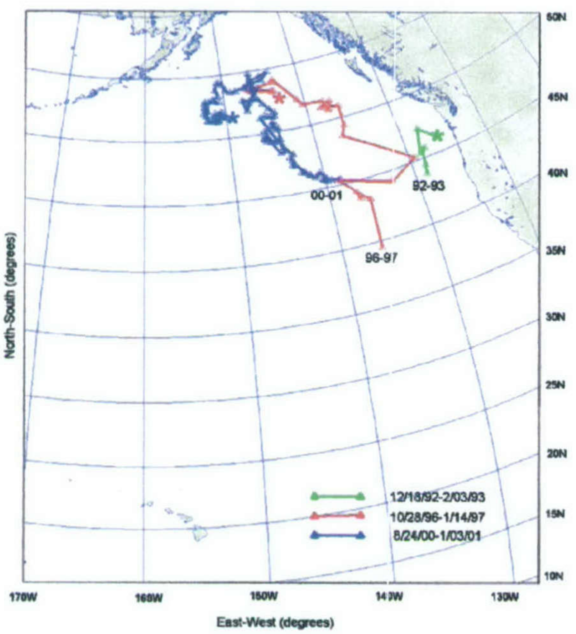

Fig. 4. Meandering tracks (A) of the 52-Hz whale for 92–93, 96–97, and 00–01. Daily calling positions are marked. Stars indicate the start of tracks.

crossed the most. The N–S tracks each were different, but when added together, they had the most time in many areas partly because there were twice as many tracks in this category. Otherwise, there did not appear to be any localized habitat preferences.

4. Discussion

The recognition of the unique 52-Hz whale calls recorded by US Navy SOSUS and other arrays over a 15-year period (1989–2004) with tracking of the source during the last 12 years has provided an unusual opportunity to document the seasonal activities of what we believe to be an individual whale. This is an example of acoustic tracking at its best, taking advantage of well-calibrated, well-placed acoustic hydrophone systems, and highly trained and experienced trackers. In contrast to these long (up to 11,000-km and 176-day) acoustic tracks of the 52-Hz whale, the usual acoustic tracking opportunity for an individual whale lasts hours at best (cf., Watkins and Schevill, 1977; Clark, 1989; McDonald et al., 1995), and the recognition of the individual being tracked often relies on non-acoustic identifiers, such as visual marks (Edds, 1982; Clark and Fristrup, 1997; McDonald, et al., 2001). The exception has been the tracking of recognizably distinct or relatively isolated sources such as the Atlantic blue whale tracked using SOSUS (Clark, 1995).

We do not know the species of this whale, whether it was a hybrid or an anomalous whale that we have been tracking. It is perhaps difficult to accept that if this was a whale, that there could have been only one of this kind in this large oceanic expanse, yet in spite of comprehensive, careful monitoring year-round, only one call with

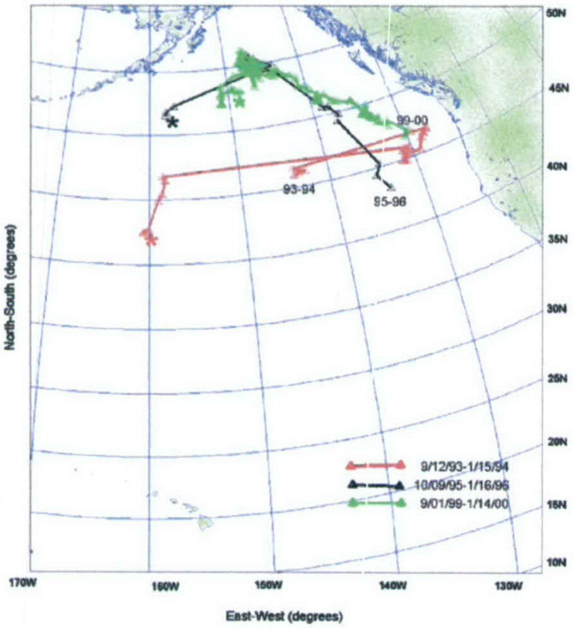

Fig. 5. West-east tracks (B) of the 52-Hz whale for 93–94, 95–96, and 99–00. Daily calling positions are marked. Stars indicate the start of tracks.

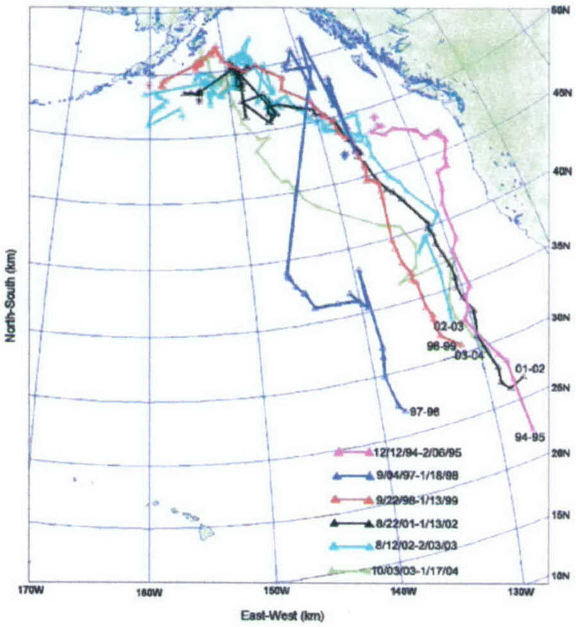

Fig. 6. North–south tracks (C) of the 52-Hz whale for 94–95, 97–98, 98–99, 01–02, the meandering and north-south (A/C) track of 02–03, and 03–04. Daily calling positions are marked. Stars indicate the start of tracks.

these characteristics has been found any where, and there has been only one source each season. The 52-Hz calls have been distinct from those of the other species monitored systematically in the same waters by the same equipment during the same time periods (cf., Watkins et al., 2001). Although the calls had a repetitive, low- frequency tonal character similar to many baleen whale sounds, they were not particularly like any sounds so far identified from those species (Watkins and Wartzok, 1985; Watkins et al., 1992; Clark and Ellison, 2004). In addition, the variable tracks of the 52-Hz whale and the apparent lack of specific habitat preferences also were different from those of the other species monitored in the same waters (Watkins et al., 2000a, b; Moore et al., 2002). Although the 52-Hz calls did not match those from any other species, they did not necessarily represent a different species, but perhaps some anomalous or hybrid individual with a modified call.

It is unusual to recognize the call of an individual whale more than a few hours. Although not recognized as individuals, sperm whales have been followed for days by acoustic tracking of sounds from groups as they moved together (cf., Whitehead and Weilgart, 1991), and during particular behaviors individual sperm whales were identified and tracked for short periods by their sounds (Watkins and Schevill, 1977). Though not tracked, calls during certain behaviors by different dolphin species have allowed recognition of individuals over long time periods (cf. Sayigh et al., 1995). Also, a number of cetacean species have been followed by tag signals for long periods while their sounds have been monitored (cf., Watkins et al., 1999). However, recognizable individual distinctions in sounds that could be followed by acoustics alone to provide positive tracking of individuals over significant periods have not been found.

The usual impediments to successful acoustic tracking of underwater biological sources include detectable level of calls above background noise on all systems needed for tracking, the presence of noise and other sounds with competing spectra, and the inability to distinguish the calls of the

Table 3
Start and end dates with positions and percent of calling days for each of the seasonal tracks of the 52-Hz whale

Track	Start	Lat.	Long.	Track/calling%	End	Lat.	Long.
92–93	18 Dec.	46.3N	126W	47 days/87%	3 Feb.	43.8N	128.6W
93–94	12 Sept.	42.4N	160.6W	127/17%	16 Jan.	45.9N	143.9W
94–95	12 Dec.	48.5N	133.2W	57/47%	6 Feb.	22.2N	126.9W
95–96	9 Oct	51.5N	158.1W	101/19%	18 Jan.	43.2N	133.8W
96–97	28 Oct.	53.2N	143.5W	78/33%	14 Jan.	39.5N	135.9W
97–98	4 Sept.	47.5N	136.7W	136/30%	18 Jan.	26.8N	137.8W
98–99	22 Sept.	54.1N	158.3W	113/49%	13 Jan.	30.6N	131.6W
99–00	1 Sept.	53N	148.5W	135/72%	14 Jan.	46.6N	130.3W
00–01	24 Aug.	51.6N	150.1W	132/86%	3 Jan.	45.4N	138.4W
01–02	22 Aug.	53.5N	155.7W	144/51%	13 Jan.	26.5N	126.7W
02–03	12 Aug.	52N	157.0W	176/74%	3 Feb.	33.0N	132.0W
03–04	3 Oct.	55.8N	153.4W	106/56%	17 Jan.	29.5N	129.3W

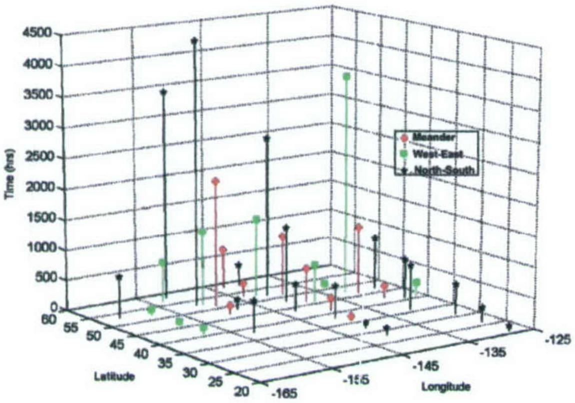

Fig. 7. Time spent in blocks of 10° × 5° shows the variable habitat of this whale. Blocks are approximately 550 km × 550 km in these northern latitudes.

individual being tracked. None of these impediments applied when tracking the 52-Hz whale: the calls were well above background noise and were received consistently on multiple hydrophone arrays, they occurred in low-noise portions of the ambient noise spectra so they were easily identified, and they were distinctly different from other sounds in the region.

Changes by the 52-Hz whale in calling and in its movements over the years perhaps were indicative of a maturing individual (Tables 2 and 3). Calling periods became more consistent with fewer gaps as the seasons progressed, generally, becoming longer with increased percentage of calling and fewer long initial gaps during calling periods. There also was a gradual 2 Hz decrease in the primary frequency of the calls over the 15 years of monitoring. The later tracks in each category were likely to be longer and faster. As years passed, there were more long treks to the south, with 5 of the last 7 tracks having this pattern, including all of the last 3, perhaps suggesting the beginning of a more organized southward migratory pattern. Possibly this also was indicated by the development of a more regular seasonal calling pattern with increasing southerly treks during the last weeks of each track.

The Navy hydrophone systems allowed convenient monitoring and tracking of the 52-Hz whale calls. Using beam-formed processing of data from large arrays deployed in deep water permitted consistent detection of the sounds on multiple arrays at long ranges. These systems assured accurate, repeatable source positions because of their well-tested calibrations. The lack of calls before and after tracking periods appeared to be because the whale was not producing calls, and not due to the lack of the ability of the monitoring equipment to detect the sounds. As the tracks demonstrated, the monitoring system was not limited geographically, and appeared to detect these calls, usually on multiple arrays, whenever calls were produced in these deep-water regions.

This series of long tracks of the 52-Hz whale during 12 successive years demonstrates the potential of such underwater sound systems to follow and describe acoustic behaviors of open ocean whales—probably not possible any other way. With the recognition of distinctive features in sounds from individuals or groups, their normal activity would be detailed by acoustic tracking, with no disturbance.

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Appendix. Track details

The **92–93** meandering track (**A**) spanned 47 days (within a 63-day calling period) and covered 708 km (Fig. 4). Although calling began on 7 December 1992 (46.3°N, 126°W), the whale remained in essentially the same waters for the next 10 days. Then on 18 December, tracking began as the whale started to move. Tracking continued until 3 February, although significant movement was recorded on only 6 days during this period. Calling ended on 10 February 1993 (43.8°N, 128.6°W). Calls were recorded on (87%) 55 of the 63-day calling period, and the whale was tracked for 47 days (Fig. 2). The track was confined to an area of approximately 400 km north-to-south by 300 km west-to-east. Speeds during the 47-day period of tracking averaged 0.7 km/h (median 0.8, SD 0.33) for an average daily distance of 15 km.

The **93–94** west–east track (**B**) spanned 127 days and covered 4891 km, but had less than 480-km north–south travel (Fig. 5). This was the second season that this whale was observed to move, and calling was sporadic although distinctive. Calling began on 12 September (42.4°N, 160.6°W) and stopped after only 6 days. Then 78 days later, calling resumed on 7 December (46.4°N, 127.5°W) and continued sporadically until 16 January (45.9°N, 143.9°W) including sporadic gaps in calling of 1–13 days. Calls were recorded on only (17%) 21 of the 127-day calling period. The whale had started calling near 160°W, traveled quietly eastward to 127°W, the general area of its meandering in 92–93, and then it returned halfway back to its starting point. Speed averaged 2.5 km/h (median 2.1, SD 1.56) for an average daily distance of 39 km.

The **94–95** north–south track (**C**) spanned 56 days and covered 3868 km. The track included north–south travel of more than 2800 km but east–west movement of less than 800 km overall (Fig. 6). The whale started calling on 12 December (48.5°N, 133.2°W), and went eastward to the general area visited the previous 2 years (46.5°N, 126.5°W). It turned on 8 January to travel southward until 6 February (22.2°N, 126.9°W). Calls were recorded on (47%) 26 of the 56-day calling period, interspersed by 1–5-day gaps in calling. Speed averaged 3.8 km/h (median 3.1, SD 2.87) for an average daily distance of 69 km.

The **95–96** west–east track (**B**) spanned 101 days and covered 3160 km within a broad north–south range of 1400-km (Fig. 5). Calling started on 9

October (51.5°N, 158.1°W) and stopped after only 2 days. Calling resumed on 16 November after 33 days of silence with the whale meandering 470 km to the northeast (55.8°N, 146.8°W). The whale then traveled eastward and southward about 1400 km to end on 18 January (43.2°N, 133.8°W). Calls were recorded on (19%) 19 of the 101-day calling period, interspersed by periods of 1–14-day gaps in addition to the initial gap of 33 days. Speed averaged 2.6 km/h (median 1.3, SD 3.33) for an average daily distance of 31 km.

The **96–97** meandering track (**A**) spanned 78 days and covered 4295 km within an area of approximately $1500 \times 1700\,\text{km}^2$, including a southeastward component (Fig. 4). Calling began on 28 October (53.2°N, 143.5°W), continued with sporadic gaps of 1–10 days, and ended on 14 January (39.5°N, 135.9°W). Calls were recorded on (33%) 26 of the 78-day calling period. Speed averaged 3 km/h (median 2.3, SD 2.31) for an average daily distance of 55 km.

The **97–98** north–south track (**C**) spanned 136 days and covered 8447 km in two separate areas (Fig. 6). Calling began on 4 September (47.5°N, 136.7°W) with the whale moving northward approximately 960 km (to 56.7°N) and meandering in that northern area until at least 27 November (54.2°N, 138.8°W). Except for a few calls on 27 November, the whale was quiet for 42 days (2 Nov.–14 Dec.), then it resumed calling and meandering again in a second area, 1700 km to the south (39°N, 146.6°W). Over the last weeks of its track, the whale moved steadily southward until 18 January (26.9°N, 137.8°W). Calls were recorded on (30%) 41 of the 136-day calling period. Speed over this entire second longest track averaged 3.4 km/h (median 2.3, SD 3.73) for an average daily distance of 62 km.

The **98–99** north–south track (**C**) spanned 113 days and covered 4770 km. The track started as a meander in northern waters, went farther northeast into the Gulf of Alaska, and then turned for a 2900-km trek southward (Fig. 6). Calling began on 22 September (54.1°N, 158.3°W), and was intermittent with sporadic gaps of up to 16 days through November, then continued calling through 13 January (30.6°N, 131.6°W). Calls were recorded on (49%) 55 of the 113-day calling period. Speed averaged 2.9 km/h (median 2.1, SD 2.49) for an average daily distance of 42 km.

The **99–00** west–east track (**B**) spanned 135 days and covered 5916 km as it meandered slowly eastward in northern waters (Fig. 5). Calling started on 1 September (53°N, 148.5°W), and the whale was tracked northeastward and then southeastward to end on 14 January (46.6°N, 130.3°W). Calls were recorded on (72%) 97 of the 135-day calling period, with 1–4 days of silence mainly toward the end of the track. Speed averaged 2.4 km/h (median 1.5, SD 2.73) for an average daily distance of 44 km.

The **00–01** meandering track (**A**) spanned 132 days and covered 6019 km. The track was confined to waters more than 1000 km offshore and turned slowly southeastward (Fig. 4). Calling started on 24 August (51.6°N, 150.1°W), continued regularly during most of the track, and ended on 3 January (45.4°N, 138.4°W). Calling was recorded on (86%) 114 of the 132-day calling period. Speed averaged 1.9 km/h (median 1.7, SD 1.23) for an average daily distance of 46 km.

The **01–02** north–south track (**C**) spanned 144 days and covered 7293 km. The track began with some meandering in northern waters, then it went southward (Fig. 6). Calling started on 22 August (53.5°N, 155.7°W) and stopped for 9 days until 30 August (53.6°N, 153.5°W). Calling resumed 53 days later on 23 October (55°N, 149.3°W) with the whale meandering in more northerly waters until it turned toward the south on 7 December (51.8°N, 145.1°W). The whale continued steadily southward until 12 and 13 January when the track turned toward the east, and calling ended (26.5°N, 126.7°W). Calling was recorded on (51%) 74 of the 144-day calling period. Speed averaged 3.5 km/h (median 3.2, SD 2.31) for an average daily distance of 51 km.

The **02–03** track had both meandering and north-south (**A/C**) components. During the first 100-day meandering portion, the whale traveled 5849 km and averaged 58 km/day, and during the last 76-day N–S portion, the whale traveled 5213 km and averaged 69 km/day. The full track spanned 176 days and covered 11,062 km. This combined track was the longest in both duration and distance (Fig. 6). Calling started in northern waters on 12 August (52°N, 157°W, and over the next 3 months, the whale meandered slowly northeastward and then southeastward. Then, beginning on 19 November (52°N, 147°W), the whale turned southward and changed to the N–S travel mode until calling stopped on 3 February (33°N, 132°W). During the full track, calling was recorded on (74%) 129 of the 176-day calling period. For the first meandering portion of the track, speed averaged 3.0 km/h (median 2.1, SD 3.3), and during the N–S portion speed, speed averaged 3.4 km/h (median 2.3, SD 4.5). For the full track, speed averaged 3.2 km/h (median 2.2, SD 3.8) for an average daily distance of 63 km.

The **03–04** north–south track (C) spanned 106 days and covered 5789 km, and started farther offshore than previous north–south tracks (Fig. 6). Calling began on 3 October in northern waters (55.8°N, 153.4°W) and continued for a short period with 1 day of silence and slow movement only until 8 October. During the subsequent 39-day gap and the next 20 days of calling which resumed on 17 November (54.5°N, 151.6°W), there was only continued slow movement. Then on 6 December, the whale began traveling steadily south-southeastward until calling stopped on 17 January (29.5°N, 129.3°W). Calling was recorded on (56%) 59 of the106-day calling period. Speed averaged 3.8 km/h (median 2.9, SD 3.6) for an average daily distance of 55 km.

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