Changes in fin whale (*Balaenoptera physalus*) song over a forty-four year period in New England waters

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Although much marine mammal research has been conducted on whales in the waters surrounding Cape Cod, Massachusetts, little work has been done on the supposed resident fin whale (*Balaenoptera physalus*) population that resides in this area. Fin whales have three different sounds in their vocal repertoire but a relatively simple song that is composed of long trains of high intensity 20-Hz pulses. Performed only by males, the song may be a reproductive display with song characteristics evolutionarily fixed within populations. In this study, fin whale vocalizations recorded in the area of Cape Cod Bay during the years 1961, 1978, 2001, and 2005 were characterized and compared within years to detect possible divergence in the male song. Reliable comparisons with the earlier data proved difficult because of small sample sizes under the chosen song parameters. However, measurements of inter-pulse interval and song length did vary significantly between the short time span of 2001 to 2005. Mean inter-pulse intervals were shorter in 2001, and song duration was longer within the 2005 recordings. Negative correlations between the center frequency and the song duration, as well as the center frequency and inter-pulse interval were also found. Although we rejected the null hypothesis that song notes and features are fixed and do not change over time, we did discover valuable information regarding the relationships between different features of fin whale song. Based on comparison of the temporal and individual variation observed in our data with those collected on a population in Bermuda, it is unclear whether vocal characteristics are distinct and could be an identifying feature of separate breeding populations.

Introduction

Baleen whales, or mysticetes, are generally thought to be social mammals whose vocalizations can be heard over very long distances (Payne and Webb 1971). The ability to communicate despite huge territory ranges allows these cetaceans to maintain social cohesion even when individuals are not in physical proximity of one another (Notarbartolo-di-Sciara et al. 2003). Acoustic signals have also long been thought to hold utility as a source of information from which to learn about population boundaries for management and conservation purposes (Payne and Guinea 1983). Presumably due in large part to high anthropogenic disturbance (McDonald and Fox 1999), many species
of large cetaceans have been deemed endangered or vulnerable and face a very high risk of extinction in the wild (IUCN 2006). To accurately assess the status of large cetaceans and work towards their preservation, it has become increasingly important to have reliable methods of estimating the size, density, and distribution of various populations (Hayes et al. 2000).

Traditional methods of population estimates have relied almost exclusively upon visual surveys, which are expensive, labor intensive and not always accurate due to temporal and spatial sampling constraints (Moore et al. 1999). Visual survey counts of sighted animals in a particular area of open ocean may also not be indicative of the overall population. In addition, the presence of vessels and the noise associated with them have been shown to disturb natural cetacean behavior (Watkins 1986). Underwater passive acoustics offers an alternative method of gathering data on cetaceans that can be combined with other sources of information to provide a better overall understanding of the animals and the viability of their populations (Moore et al. 1998). Of particular interest here are the baleen whales who reside mostly in pelagic environments and have proven difficult to assess through traditional means, such as the fin whale (*Balaenoptera physalus*) and blue whale (*Balaenoptera musculus*) (McDonald and Fox 1999). The use of long range passive acoustics has the potential to reveal valuable information regarding their natural ecology, behavior, and population dynamics (Moore et al. 1998).

As little as twenty-five years ago, fin whales were thought to be nearly impossible to study because of the animals’ strongly negative reactions to approaching vessels (Watkins 1986). Since then, fin whales have apparently become more accustomed to anthropogenic presence. They are now more likely to “ignore” vessels that are thirty or
more meters away, although vocalizations still cease when the animals are disturbed (Watkins 1986). Although this behavioral change has allowed scientists to gain a better perspective through direct observation on the ecology of fin whales, anthropogenic disturbance still seems to interrupt normal fin behavior (Watkins 1986). However, of all cetaceans, fin whales and blue whales are known to produce the lowest frequency vocalizations at the highest source levels (Payne and Webb 1971, Charif et al. 2002), which provides ample opportunity to study these species through long-range passive acoustics without disturbing their natural behavior.

Next to most other baleen species, fin whales make relatively simple sounds (Thompson et al. 1992). Their song note repertoire is composed of three different note types which are arranged in long patterned sequences, referred to as “songs” (Clark et al. 2002, Hatch 2004). Note types include 20-Hz pulses, “backbeats,” and “upsweeps” (Hatch 2004). Backbeats, which are produced at 15-18 Hz and the rarely seen upsweeps that occur between 134-142 Hz have lower source levels than the 20-Hz pulses and are also less well documented (Clark et al. 2002, unpublished data).

Most typically, fin whales produce series of high-intensity notes within the 18 – 25 frequency band (Watkins et al. 1987, Notarbartolo-di-Sciara et al. 2003). Referred to as “20-Hz pulses,” these note sequences are composed of downsweeps that have constant inter-pulse intervals and an almost mechanical regularity (Watkins 1981, Watkins et al. 1987). Sequences of 20-Hz pulses usually occur in long bouts or “trains” and can continue for more than 32 hours (Watkins et al. 1987) at source levels of 159 to 185 dB (Charif et al. 2002, Notarbartolo-di-Sciara et al. 2003). Characteristics of 20-Hz sequences can differ in the inter-note interval, number of notes per song, number of songs
within a bout, the song duration, number of note types per song, and note clustering patterns.

The functional significance of fin call variability is unknown (Clark et al. 2002). However, the many advantages to producing calls at 20 Hz make fin whale songs extremely well suited to long-distance communication in deep ocean environments (Payne and Webb 1971). Advantages to vocalizing in the narrow frequency band around 20 Hz include the fact that such calls lie below storm-generated noise, lose little to no energy from reflection off the seafloor or sea surface, have low attenuation with distance, and are within the most optimal octave band for long-range sound propagation in polar ocean conditions (Payne and Webb 1971).

The prevalence of 20-Hz pulses over temperate latitude ranges is highest during the winter and early spring months and lowest in the late spring through the early summer (Thompson and Friedl 1982, Watkins et al. 1987, Moore et al. 1998). Watkins et al. (1987) proposed that the 20-Hz sounds were male reproductive displays through a synthesis of acoustic records from Bermuda, and because it was deduced that the breeding season was coincided with these peaks in stereotypic vocal behavior. This hypothesis of male vocal breeding displays was supported by Croll et al. (2002), who determined through the specific correlation of singing behavior and molecular data that only male fin whales sing. Confusion exists as to the full function of these patterned 20-Hz vocalizations by male fins, however, since fin whales have been noted singing during the feeding season in high latitudes in late summer (Clark 1995), as well as in late winter (Clark et al. 1999). It has been suggested that while long song bouts may serve as reproductive displays (Moore et al. 1998), shorter irregular pulse sequences of less than
five minutes could simply be associated with feeding, socializing, or transiting animals (Watkins 1981, McDonald et al. 1995). However, both long and short sequences are produced by fin whales during feeding times in the late summer months and in high latitudes (Clark et al. 2002, Clark unpubl. data).

Overviews by Payne and Webb (1971) and Tyack (2000) suggested that the whales disperse widely during their mating season, with movements possibly also dictated by prey availability (Croll et al. 2002). Through their observations in the field, Watkins and Schevill (1979) noted that groups of fin whales from distances of ten kilometers away or more will travel to the same feeding area as other groups of whales. They speculated that fin whales vocalizing while feeding may alert other whales within proximity to locations of high prey concentration (Watkins and Schevill 1979). Since fin whales do not appear to have specific breeding grounds, Croll et al. (2002) proposed that vocal displays by males at feeding grounds may serve to attract females to prey aggregations from long distances.

Some populations of fin whales are thought to be residents of certain areas, such as in the Mediterranean Sea (Notarbartolo-di-Sciara et al. 2003) or the New England region. As shown by Seipt et al. (1990) and Clapham and Seipt (1991) with populations in the North Atlantic and Massachusetts Bay area, residency could be in part due to matrilineally determined site fidelity to specific feeding areas. Most of the work that has been done to define the population boundaries of fin whales has focused on both the distribution and the relatedness of individuals within their summer feeding aggregations (Agler et al. 1991, Bérubé et al. 1998). Thompson et al. (1992) suggested that specific acoustic features of vocalizations, specifically those from male reproductive displays,
could serve as a tool to indicate population identity in fin whales. The fact that fin whale song shows less inter-annual, inter-individual, and intra-individual variability than the song of other baleen species (Clark and Ellison 2003) has provided further optimism for learning about fin whale populations from acoustic data. This idea was further supported through work by Hatch (2004), who found that the measurement of time between notes during fin song is a highly significant predictor of the region from which the song was recorded, even if the males vocalizing are not necessarily closely related. If songs sung by males are a reproductive display, it would provide evidence that song characteristics may be relatively fixed on an evolutionary scale within populations (Croll et al. 2002). Such findings could have important implications for conservation purposes, as the song characteristics of individual whales could then be used to attribute them to particular populations even over large time scales.

As members of the Western North Atlantic population, fin whales from Cape Cod Bay, Massachusetts are believed to be resident to the New England region. In this study, I compared several song characteristics between different bouts of 20-Hz vocalizations by fin whales in Cape Cod Bay during the years 1961, 1978, 2001, and 2005. Measurements of the 20-Hz notes and songs included note center frequency, time between successive pulses, and song duration. Both inter-year comparisons and intra-year correlation tests were conducted to investigate whether acoustic song features were constant over this relatively short time period. My hypothesis regarding these fin whale song characteristics was that there would be no significant differences between the historical and more recent song data, which would suggest that song characteristics are uniform within distinct populations of fin whales. This prediction stemmed from the
basis that qualities utilized in reproductive displays within a population should be fixed on an evolutionary scale. In addition, there should be little selection pressure on fins to change their song, since it is already very well suited to long-distance propagation in deep ocean environments (Payne and Webb 1971). Any significant changes in the fin whales song might suggest that song characteristics are not fixed but potentially influenced by individuals from other populations or environmental conditions, including anthropogenic noise. The characterization of fin whale song within this presumed resident population over a period of forty-four years has the potential to reveal valuable information about the male song, the factors that influence it, and the next steps in effective acoustic monitoring of fin whale populations.

**Methods**

**Acoustic data collection**

Data from eight days in mid-March 2001 and five days in early April 2005 were chosen for acoustic analysis, as well as two recordings from the winter months of 1961 and one short recording from 1978. The fin whale acoustic data from 2001 and 2005 were recorded in the area of Cape Cod Bay, Massachusetts (Figure 1) by scientists associated with the Cornell Bioacoustics Program. Originally for use in the monitoring of area right whales, data were collected using several autonomous sea floor recording devices, referred to as “pop-ups” (Clark et al. 2002, Clark and Clapham 2004. Arrays of three pop-ups in 2001 and five pop-ups in 2005 were deployed in Cape Cod Bay to provide multi-channel sound data for analysis (Figure 2). Acoustic data recorded on all channels simultaneously over a period of several weeks in both March 2001 and April 2005 at a sampling rate of 2000 Hz.
The small amount of fin whale acoustic data from 1961 and 1978 were generously provided by W.E. Watkins from the Woods Hole Oceanographic Institution (WHOI). These data were recorded in the Nantucket Shoals region by Drs. Schevill and Watkins during the early winter months of 1961 and 1978, although the exact dates of collection are unknown. Recordings totaled 340 hours of sound in which fin whale vocalizations were either known or expected to be present (Table 1). All sound samples are archived within the Cornell Laboratory of Ornithology’s Bioacoustics Research Program (http://www.birds.cornell.edu/brp/). For this inter-year study, it would have been preferable to compare acoustic data from several years and one location during the exact same time of year. However, this was not possible, as there were no recordings available from early spring in 1961 or 1978. Recordings in 2001 were only made during the month of March, and in 2005, a complete array of pop-ups was not arranged until the first days of April.

Figure 1. Map of Cape Cod Bay and Nantucket Shoals region, location from which acoustic data were recorded in years 1961, 1978, 2001, and 2005.
Figure 2. Orientation of the five autonomous underwater recording devices (pop-ups) used in Cape Cod Bay, Massachusetts in 2005.

Table 1. Dates and locations of recordings of fin whale vocalizations, including the duration of samples and number of songs detected per day in Cape Cod Bay, MA (CCB) and Nantucket Shoals region (NS).

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Duration of sample (hours)</th>
<th>Songs detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>NS</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>1978</td>
<td>NS</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>10 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>54</td>
</tr>
<tr>
<td>11 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>81</td>
</tr>
<tr>
<td>12 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>105</td>
</tr>
<tr>
<td>13 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>129</td>
</tr>
<tr>
<td>14 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>61</td>
</tr>
<tr>
<td>15 March 2001</td>
<td>CCB</td>
<td>24</td>
<td>57</td>
</tr>
<tr>
<td>05 April 2005</td>
<td>CCB</td>
<td>24</td>
<td>111</td>
</tr>
<tr>
<td>06 April 2005</td>
<td>CCB</td>
<td>24</td>
<td>102</td>
</tr>
<tr>
<td>10 April 2005</td>
<td>CCB</td>
<td>24</td>
<td>109</td>
</tr>
<tr>
<td>16 April 2005</td>
<td>CCB</td>
<td>24</td>
<td>89</td>
</tr>
<tr>
<td>17 April 2005</td>
<td>CCB</td>
<td>8.5</td>
<td>3</td>
</tr>
</tbody>
</table>
Fin whale data collection

Acoustic data were visualized using the Cornell-developed sound display and measurement program XBAT (www.xbat.org), written by Harold Figueroa and augmented by measurement sub-routines by Kathy Cortopassi of the bio-engineering staff at the Cornell Bioacoustics Research Program and run within MATLAB (The Mathworks, Inc., 1999). To maintain standard spectrogram frequency and time resolution for the data display among the different recordings, a Fast Fourier Transform (FFT) of 4096 and an overlap (hop length) of 0.5 seconds were kept constant when browsing data. Sound recordings were browsed manually for the years 1961, 1978, and 2005 to locate fin whale vocalizations and make general observations. All notes within the 20-Hz frequency range that were determined to be fin whale vocalizations were manually marked and labeled (i.e., annotated). Automatic detection, a special feature within XBAT (www.xbat.org), was used to locate and mark the 20-Hz pulses in the 2001 data. Automatic detection parameters were determined through the application of a 20-Hz pulse as the detection “template.” Sounds similar enough in shape and frequency range to the template were automatically marked as fin whale vocalizations. Data from 2001 were then browsed manually to make any necessary corrections to the automatic detections.

During certain periods, pauses in song on one channel but continuation on another, or differences in song rhythm, indicated that multiple singers were vocalizing. In such instances, 20-Hz pulses were attributed to a certain individual (“Fin 1” or “Fin 2”) (Figure 3). When two or more individuals were detected on the same channel, they were distinguished by the appearance of their notes, the apparent time between pulses,
the beginning and end frequency patterns, and through listening and comparing the acoustic qualities of the vocalizations. Periods of time during which individuals could not be objectively differentiated from one another were omitted from all analysis, as were periods of very low signal to noise ratios. While the presence of backbeats and 40-Hz downsweeps were noted occasionally, in this study, analysis was limited strictly to the more typical 20-Hz pulses. A total of 13,695 notes in the 20-Hz frequency range were either manually or automatically detected, marked, and attributed to individual animals from the recordings over all four years (Table 1). Unfortunately, because acoustic data were originally collected for use in right whale study, documentation of fin whale sightings in the area are limited for April 2005 and are not available for years 1961, 1978, and 2001. Without more accurate visual data or identification data on individual animals, it is difficult to make an estimation of the number of vocalizing fin whales that were in the area or the number of times the same individual was recorded.

Figure 3. Spectrogram of two different fin whale singers on channels one and three at 20-Hz. X-axis is time, y-axis is frequency in kHz. Boxes are drawn around selected notes on each channel to emphasize the presence of two singers.
Fin whale data analysis

Three measures were used to compare fin whale song between and within years, including center frequency (Hz), inter-pulse interval (seconds), and the number of notes per song, as an indication of song duration. Center frequency was chosen as a comparative measurement, since it is presumably an adaptation for long-range communication by fin whales and should not change much over time. Inter-pulse interval, or the time between successive notes in a song, is one of the more variable and traditionally measured features in fin whale vocalizations. Song duration was chosen because of its potential to undergo yearly changes and because it may be an indication of a singer’s endurance and mate quality. Other possible measurements, such as note duration or total energy, were not included in analysis, since the length and strength of the vocalizations can vary depending on the singer’s distance from the recorder.

Similarly, upper, lower, and peak note frequencies were not compared, as acoustic signals deteriorate with distance.

Each note’s center frequency (Hz) and center time (seconds) were measured within XBAT (www.xbat.org), using ninety-five percent of the note’s total energy. Measurements were exported from XBAT (www.xbat.org, http://www.birds.cornell.edu/brp/research/algorithm/energy-distribution-measurement) and MATLAB (The Mathworks, Inc., 1999) as tables into EXCEL (Microsoft Office, Inc. 1998). Here the inter-pulse interval was calculated for each note by subtracting the center time of the note preceding it from its own center time. In order to compare songs between the four years, data were organized by separating the sequences of 20-Hz pulses into distinct songs through a program written and run through MATLAB (The
Mathworks, Inc., 1999) by Carlos Botero (Dept. Neurobiology and Behavior, Cornell University). A song was defined as a sequence of no less than 3 pulses, each with an inter-pulse interval of no more than 15 seconds. For each song, the number of notes contained within the song was determined, and the measurements from each of these notes were averaged.

A total of 904 songs were differentiated from one another, and mean measurements corresponding to each song were organized and stored as a text file to be analyzed in MINITAB version 14.20 for Windows. While 487 and 414 songs were identified within the recordings from 2001 and 2005, respectively, no songs were identified for the 1978 sample, and only three songs were found in the two samples from 1961 using the aforementioned parameters (Table 1).

The matrix of the 904 songs and each of their mean measurements was used to perform inter-year comparisons and intra-year correlation tests within MINITAB (version 14.20 for Windows). Pair-wise comparisons for center frequency, inter-pulse interval, and song duration were done between each of the years that contained songs (1961, 2001, 2005) using a one-way analysis of variance with Tukey 95% simultaneous confidence intervals. Pearson correlation tests were then conducted to identify any relationships between the chosen song characteristics within each of the years 1961, 2001, and 2005.
Results

Similar to past descriptions of fin whale song, the recorded vocalizations from Cape Cod Bay in the years 1961, 1978, 2001, and 2005 occurred in long, patterned sequences with an almost mechanical regularity. Signal energy was between 15 and 23 Hz, and pulse trains had relatively constant time intervals between successive notes within years, varying from an average of 8.5 seconds in 1961 to 15.4 seconds in 2005. Despite the same basic song pattern, however, there were visible differences in the note and song characteristics between years. In addition, sample sizes for songs were comparable in 2001 and 2005, but only three songs were detected in the 1961 data, and no songs were detected from 1978. Mean song measurements and their standard deviations for the years 1961, 2001, and 2005 can be seen in Table 2.

Inter-year comparisons were made based on mean song measurements for the detected songs from years 1961, 2001, and 2005, including center frequency, inter-pulse interval, and the number of notes per song. Song from 1961 was found to be statistically different from both the 2001 and 2005 songs in all three measurements. However, the very small sample size of only three songs from 1961 must be taken into account. Without additional information regarding the vocalizing animals, we cannot eliminate the possibility that all three songs came from a single individual and would therefore probably not be indicative of all fin whale song from Cape Cod Bay during the year 1961. Between 2001 and 2005, both the length of the inter-pulse interval and the number of notes per song were statistically different, with song from 2001 being shorter, and song from 2005 having longer inter-pulse intervals. Pearson correlation tests revealed negative
relationships between the center frequency and song length, as well as between center
frequency and inter-pulse interval in the years 2001 and 2005.

Table 2. Mean measurements in fin whale song for recordings from Cape Cod Bay from

<table>
<thead>
<tr>
<th></th>
<th>1961</th>
<th>2001</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td><strong>measurement</strong></td>
<td><strong>Mean</strong></td>
<td><strong>measurement</strong></td>
</tr>
<tr>
<td><strong>Standard</strong></td>
<td><strong>deviation</strong></td>
<td><strong>deviation</strong></td>
<td><strong>deviation</strong></td>
</tr>
<tr>
<td><strong>Number of</strong></td>
<td><strong>songs</strong></td>
<td><strong>487</strong></td>
<td><strong>414</strong></td>
</tr>
<tr>
<td><strong>Center</strong></td>
<td><strong>frequency</strong></td>
<td><strong>17.9</strong></td>
<td><strong>20.1</strong></td>
</tr>
<tr>
<td><strong>(Hz)</strong></td>
<td><strong>0.8</strong></td>
<td><strong>1.3</strong></td>
<td><strong>1.1</strong></td>
</tr>
<tr>
<td><strong>Inter-pulse</strong></td>
<td><strong>interval</strong></td>
<td><strong>8.50</strong></td>
<td><strong>14.65</strong></td>
</tr>
<tr>
<td><strong>(sec)</strong></td>
<td><strong>1.58</strong></td>
<td><strong>0.82</strong></td>
<td><strong>0.99</strong></td>
</tr>
<tr>
<td><strong>Number of</strong></td>
<td><strong>notes per</strong></td>
<td><strong>52.3</strong></td>
<td><strong>8.0</strong></td>
</tr>
<tr>
<td><strong>song</strong></td>
<td><strong>42.2</strong></td>
<td><strong>7.7</strong></td>
<td><strong>19.9</strong></td>
</tr>
</tbody>
</table>

**General Observations by Year**

Fin whale song from 1961 was composed of pulses with an average center
frequency of 17.9 Hz (s.d.=0.8, N=3) (Table 2), often associated with harmonic
downsweeps of shorter duration (Figure 4). The harmonic downsweeps ranged from 29-
43 Hz and had durations of about 1.2 seconds each. Only one channel of data was
available, so it is possible that more than one singer was recorded, although it would have
been very difficult to distinguish between individuals because of the background noise.

![Figure 4. Fin whale pulse train with harmonics, recorded in 1961 by scientists with the Woods Hole Oceanographic Institute in Cape Cod Bay.](image)
The recording provided from 1978 was very short and highly contaminated with noise in most parts. No “songs” were detected using the chosen parameters, although it did appear by the appearance of the spectrograph that multiple singers were vocalizing, because the rhythm of 20-Hz pulses was not regular during the time of recording (Figure 5). Because of the difficulty in differentiating between singers, the data were not sufficient to identify individual songs. A point of interest within the 1978 data, however, was that the “20-Hz” pulses were actually within the 21-32 frequency range, much higher than any of the other recordings described here. There were no downswept harmonics in the 40-Hz range or backbeats observed.

Figure 5. Recordings of multiple individuals vocalizing within a higher frequency range than the “typical” 20-Hz pulse song by fin whales, recorded in 1978 in Cape Cod Bay by scientists at the Woods Hole Oceanographic Institution.

Data from the year 2001 was available starting on the eighth of March, but no 20-Hz pulses were detected until the 10th of March. Series of 40-Hz downsweeps, however, were very common on March 9th and into the next few days of recordings. Downsweeps were between 35 and 46 Hz with durations of approximately two seconds each. They occurred in series with the same mechanical regularity and similar inter-pulse intervals as the later vocalized 20-Hz pulses. Often during the first couple days in which 20-Hz pulses were observed, 40-Hz downsweeps were also present as harmonics of the pulses (Figure 6). Backbeats were not noted as a regular occurrence before or after 20-Hz
pulses. Recordings from 2001 generally included only one vocalizing animal at a time. Only in a few instances were multiple singers noted. The pulses also often seemed to occur at lower source levels than those from the 2005 data (due either to the animals vocalizing less loudly or being farther away from the pop-up recorders).

![Example of 20-Hz pulses with 40-Hz 2nd harmonic in fin whale song from Cape Cod Bay on March 10th 2001.](image)

Acoustic recordings from 2005 frequently included multiple singers vocalizing at the same time. Vocalizations were regular, often at high source levels, and less choppy than some of the 2001 song. No 40-Hz harmonic downsweeps were noted, although the presence of backbeats either before or after 20-Hz pulses was not uncommon. Mean values of note center frequency, inter-pulse interval, and song length can be seen in Table 2.

**Comparisons of note and song characteristics between years**

Pair-wise comparisons were conducted for the three note and song measurements using Tukey 95% simultaneous confidence intervals. Mean song inter-pulse interval was significantly different between all three years (Table 2, Figure 7). Despite the small sample size, the especially large change in inter-pulse interval from 1961 (8.50 sec., s.d.=1.58, N=3) to 2001 (14.65 sec., s.d.=0.82, N=487) and 2005 (15.41 sec., s.d.=0.99,
N=414) is notable. Years 2001 and 2005 had a tighter confidence interval than either did with year 1961 but were still significantly different from one another (Figure 7). Interestingly, we found similar patterns of inter-pulse interval becoming longer in duration throughout the recording periods in both March 2001 and April 2005 (Figure 8), indicating that there may also be quite a bit of inter-seasonal variation in the inter-pulse intervals.

![Interval Plot of Inter-pulse Interval vs Year](image)

Figure 7. A.) Spread of inter-pulse intervals in seconds between 20-Hz pulses in fin whale song from Cape Cod Bay. B.) Mean inter-pulse intervals and their confidence intervals in years 1961, 2001, and 2005.
In comparing the center frequency of song notes, males from 1961 vocalized at a significantly lower frequency than those from either 2001 or 2005 (Figure 9). The mean center frequency in 1961 was determined to be 17.9 Hz (s.d.=0.8, N=3), while singers in 2001 and 2005 vocalized at 20.1 Hz (s.d.=1.3, N=487) and 20.0 Hz (s.d.=1.1, N=414), respectively. There was no significant change in center frequency between years 2001 and 2005.
As with the inter-pulse interval, there was a significant difference in the number of notes per song between all years. However, the length of songs varied greatly within each year, causing very large spreads and standard deviations in the comparisons (Figure 10). The average number of notes per song in 1961 was 52 (s.d.=42, N=3). In 2001, mean song length was shorter, with the average number of notes at 8 (s.d.=8, N=487), and in 2005, songs were slightly longer with 14 notes per song (s.d.=20, N=414).
Correlations in note and song characteristics within years 1961, 2001, and 2005

Song within each year was then examined for correlations between the chosen measurements. In 2001, center frequency was negatively correlated with the number of notes per song (Pearson’s correlation, $r=-0.16$, $P$-value=0.000), as it was in 2005 (Pearson’s correlation, $r=-0.15$, $P$-value=0.000). The negative correlation between center
frequency and number of notes per song was not significant in 1961 (Pearson’s correlation, \( r=-1.0 \), P-value=0.057). Relationships in all three years are displayed by Figure 11.

Center frequency and the inter-pulse interval were also negatively correlated in 2001 (Pearson’s correlation, \( r=-0.37 \), P-value=0.000) and in 2005 (Pearson’s correlation, \( r=-0.27 \), P-value=0.000), shown by Figure 12, but not in 1961 (Pearson’s correlation, \( r=0.70 \), P-value=0.510). There was no significant correlation between the inter-pulse interval and song length in any year.
Figure 11. Correlation between the mean center frequency (Hz) and number of notes per fin whale song recorded in 1961, 2001, and 2005 in Cape Cod Bay. Each dot represents one song.
Figure 12. Correlation between the mean center frequency (Hz) and inter-pulse interval (seconds) for fin whale songs recorded in 2001 and 2005 in Cape Cod Bay. Each dot represents one song.
Discussion

In this study, fin whale vocalizations recorded in the area of Cape Cod Bay, Massachusetts during the years 1961, 1978, 2001, and 2005 were characterized. Song was compared among the 2001 and 2005 data, as well as between years 1961, 2001, and 2005 where possible. The aims of this study were two-fold, (1) to detect changes in male fin whale song over this forty-four year period and (2) to examine the relationship of song center frequency with both song length and inter-pulse interval within each year. Rejecting the null hypothesis of no significant changes in song characteristics between years would be inconsistent with the presumption that vocalizations meant for reproductive displays would be constant over short time scales. Comparison between the earlier and later data was proven difficult, as no songs were detected in 1978 under the parameters chosen. Fin whale song from 1961 had an average inter-pulse interval, center frequency, and song duration that differed from 2001 and 2005 song, although these differences could be due to a small sample size. Acoustic data in March 2001 and April 2005 were sampled in a similar fashion and during the same time of year. Songs from March 2001 were significantly shorter in duration and had smaller inter-pulse intervals than song from April 2005. Negative correlations were found both between the center frequencies and inter-pulse intervals and between the center frequencies and number of notes per song in the years 2001 and 2005.

The steady inter-pulse interval of fin whale song has proven in the past to be a reliable predictor of the region from which the song was recorded (Watkins et al. 1987, Thompson et al. 1992, Hatch 2004), despite some seasonal variation (Watkins et al. 1987, Moore et al. 1998). Fin whale song tends to be most prevalent in the winter and early
spring months (Thompson and Friedl 1982, Watkins et al. 1987, Moore et al. 1998), so for the purpose of this study, we thought that acoustic displays within the same season (i.e. March 2001 and April 2005) would be similar, even between years. However, the results presented here show that inter-pulse intervals from early spring of 2001 were significantly shorter than those of 2005. Rejection of the null hypothesis that song features would not change, these results are actually consistent with previous findings by Watkins et al. (1987). In their research, Watkins et al. (1987) found that the inter-pulse interval progressively increased over the course of the late winter months and varied largely over the rest of the season. Inter-pulse intervals remained somewhat constant during their study period of two decades for the Bermuda area, although there was significant variation from year to year and within seasons (Watkins et al. 1987). Figure 13 displays the seasonal pattern of inter-pulse interval lengths found by Watkins et al. (1987) from fin whale songs from Bermuda over a five year period (July to June 1958-59, 1959-60, 1967-68, and 1978-79, January to June 1967, and July to December 1968).

![Figure 13](image)

Figure 13. Monthly averages of inter-pulse intervals within fin whale song from Bermuda over a five-year period (July to June 1958-59, 1959-60, 1967-68, and 1978-79, January to June 1967, and July to December 1968) by Watkins et al. (1987). Pulse intervals were tallied for the month in which the bout began. Horizontal bars denote the average inter-pulse interval for the month, and the vertical bars mark the standard error of the monthly sample (Watkins et al. 1987).
In comparing the acoustic data from Bermuda to those from Cape Cod Bay, we find that the inter-pulse intervals in Bermuda are longer during the same time of year than those from song in Cape Cod Bay. Although not significantly different, Bermuda fin whale song in April had a mean inter-pulse interval about a second longer than in March (Figure 13, Watkins et al. 1987). The seasonal difference from Bermuda during Watkins et al.’s (1987) study period is similar to the increase of approximately one second in mean inter-pulse interval that we see between March 2001 and April 2005 in Cape Cod Bay. These results are consistent with the results from Watkins et al. (1987) that the inter-pulse interval varies seasonally. With the possibility for such a large change in inter-pulse interval between months and despite recordings having been from the same season, inter-year comparisons of this vocal characteristic between the months of March 2001 to April 2005 may not be reliable. Hatch (2004) found that different patterns of inter-pulse intervals can arise over the course of several years. She suggested that a dominant pattern may last several years before changing to a different pattern that will last another few years (Hatch 2004). Whether seasonal variation remains consistent over long periods of time relative to changes in mean inter-pulse intervals between years is unknown, although it would be interesting to compare recordings from mid-March and early April in Cape Cod Bay over the course of several years.

It is also important to consider that the ability of certain song features may vary seasonally in its reliability of assigning individuals to regions (Hatch 2004). For example, song from the northwest North Atlantic and western tropical North Atlantic had higher distinction and showed less variance between individuals in the late fall and early winter as opposed to the springtime (Hatch 2004). It would be useful to characterize
continual fin whale song over the course of a few years in several locations, to document and compare patterns of seasonal change within each region, as well as identify how song changes in one location might influence the song of another area. Inter-pulse intervals are thought to be the best song feature for differentiating fin whale populations, and it may be possible in the future to assign individuals to particular populations based on comparisons of inter-pulse intervals. However, it is important that we understand the regional patterns of seasonal and yearly change before prematurely attempting to define populations based on such specific song parameters.

The center frequency of fin whale song is a defining characteristic presumably because of the many advantages that vocalizing at 20 Hz has for long-range communication. Vocalizations recorded in 1961 were found to have an average center frequency of more than two Hertz less than in 2001 or 2005, and those from 1978 were considerably higher in frequency than any other year. Producing high intensity infrasonic calls probably requires a large body size, as animals most effectively produce sounds that have wavelengths equal to or smaller than their own body sizes (Bradbury and Vehrencamp 1998). Larger animals are therefore most likely better able to vocalize at lower frequencies (Bradbury and Vehrencamp 1998), so it is possible that the songs recorded in 1961 were produced by a larger animal or animals than those in 1978, 2001, or 2005. Center frequencies between 2001 and 2005 were not significantly different, so we might expect that vocalizing males within these time periods were of similar sizes.

If center frequency is indicative of body size, it may reveal information about the quality of vocalizing individuals to listeners. Especially in species with little or no male parental investment, costs of reproduction for females are very high, so it is not unlikely
that females would choose potential mates based upon certain defining criteria that would confer higher reproductive success on their offspring (Clapham 1996). Heritable qualities such as larger size, higher stamina, and better competitive abilities have been shown to increase the mating success of males in many other taxa (LeBoeuf 1974, Gosling and Petrie 1981, Clutton-Brock et al. 1982, Clapham 1996).

Song length may contain information relating to the fitness of singing humpback whales, as it could be indicative of diving ability and stamina (Chu and Harcourt 1986, Chu 1988). The number of notes per song, or song duration, in fin whales may reveal similar information regarding the stamina of a specific whale or group of individuals. Fin whale song from April 2005 was significantly longer in duration than song from March 2001. If singers from this supposed resident population were the same between both years, the change in mean song duration could indicate that with age, the males had become more experienced singers with higher stamina. The ability to maintain high regularity within a song for long periods of time could also be an indication of male quality (Clark pers. comm.). However, as with humpback whales, it may prove difficult to assign male quality to specific song lengths in fin whales, as mean song length within a population evidently varies between years (Payne et al. 1983). In terms of seasonality, the results found here are not in accordance with those of Watkins et al. (1987), who found off Bermuda that fin whale song became shorter over the course of the season. Clark (pers. comm.) has also noted that fin whale song normally tends to lesson and deteriorate through the course of the springtime in Cape Cod Bay.

Songs of different lengths could relay several types of information between communicating whales. Longer song bouts may serve as reproductive displays (Moore et
al. 1998), but shorter, irregular pulse trains could be associated with feeding, socializing, or transiting animals (Watkins 1981, McDonald et al. 1995). During peak feeding periods in the late summer months, both long and short sequences are heard, which has led to the hypothesis that vocal displays serve to attract females from long distances to prey aggregations (Croll et al. 2002). The vocalizations from March 2001 analyzed here were significantly shorter than those from April 2005. During the first few days of data collection in 2001, no 20-Hz pulses were detected. When songs were observed, they did not immediately have the mechanical regularity of the 20-Hz pulse trains observed in April 2005. The earlier vocalizations in March 2001 could possibly have offered different information to females or conspecifics than those from April 2005. They may also have been the result of newly vocalizing males or the recording of only a few individuals that were not necessarily representative of all resident males.

A negative correlation between mean center frequency and the number of notes per song was found in both 2001 and 2005. This relationship could be due to the actual physical constraints of a singing fin whale. If it is the larger animals that are able to vocalize at lower frequencies, these males may also have higher stamina and be more capable of singing for longer periods of time. Fin whales grow continually with age, so larger body size might also go hand in hand with more experience as a singer. Short song at a higher frequency may be an indication of a younger, smaller, and more inexperienced individual, whereas song of long duration sung at lower frequencies could be a sign of a larger, older male who has the ability to maintain regularity in his vocalizations for longer periods of time.
The negative correlation between center frequency and inter-pulse interval in years 2001 and 2005 may also be due to some sort of physical constraint. If smaller males are somehow able to disguise their size by singing at lower frequencies, the higher energy demand could limit how quickly they are able to vocalize again. It would be helpful to have accurate information on the corresponding song intensities, because if males sing very loudly at lower frequencies, the high amounts of energy invested into each note might require a longer recuperation period before the output of the next note. The allowance of more time between each pulse would also make the pulses more distinct to listeners at further distances from the singer.

The exact function of fin whale song remains unknown, but acoustic data have proven useful in preliminary attempts to understand their behavior and differentiate between regional fin whale populations. Although fin whale song may be an acoustic mating display by males, results of this study suggest that specific note and song features, such as center frequency, inter-pulse interval, and song duration, can differ significantly over a relatively short period of time. One explanation for the changing patterns in fin whale song from Cape Cod Bay may be the animals’ contact with vocalizing whales from other populations, as there is evidence of vocal learning in several other cetacean species (Tyack 2000). A study by Rhen and Crews (2002) also reported that mammals seem to be particularly sensitive to environmental perturbations that influence intrasexual changes in behavior. It is currently unclear as to whether shifting fin whale song is due to the incorporation of the different song features to which they are exposed, or if it is simply a result of differing environmental influences on the singers, including seasonal effects. The goal of defining population boundaries based on acoustic data requires a much better
understanding of seasonal and yearly song variation within and between regions. It is also important to consider that population boundaries are likely to be dynamic (Hatch 2004). Spatial overlap in populations is expected to vary in response to oceanographic cyclic fluctuations (Greene and Pershing 2000) and other environmental variables that would affect the availability and location of prey (Hatch 2004). Anthropogenic effects also no doubt might have a large influence on fin whale distributions and may affect the degree to which individuals from different populations come into contact with one another, either physically or acoustically (Hatch 2004). A thorough study of continuous fin whale acoustic data over the course of several years in adjacent regions would prove extremely useful to characterize seasonal and annual variability in song, as well as to help identify anthropogenic, environmental, and inter-population influences on song patterns.