

Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean

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(Received 12 September 2003; revised 15 January 2004; accepted 19 January 2004)

Beginning in February 1999, an array of six autonomous hydrophones was moored near the Mid-Atlantic Ridge (35°N–15°N, 50°W–33°W). Two years of data were reviewed for whale vocalizations by visually examining spectrograms. Four distinct sounds were detected that are believed to be of biological origin: (1) a two-part low-frequency moan at roughly 18 Hz lasting 25 s which has previously been attributed to blue whales (*Balaenoptera musculus*); (2) series of short pulses approximately 18 s apart centered at 22 Hz, which are likely produced by fin whales (*B. physalus*); (3) series of short, pulsive sounds at 30 Hz and above and approximately 1 s apart that resemble sounds attributed to minke whales (*B. acutorostrata*); and (4) downswept, pulsive sounds above 30 Hz that are likely from baleen whales. Vocalizations were detected most often in the winter, and blue- and fin whale sounds were detected most often on the northern hydrophones. Sounds from seismic airguns were recorded frequently, particularly during summer, from locations over 3000 km from this array. Whales were detected by these hydrophones despite its location in a very remote part of the Atlantic Ocean that has traditionally been difficult to survey. © 2004 Acoustical Society of America. [DOI: 10.1121/1.1675816]

PACS numbers: 43.80.Ka, 43.30.Sf [WA]

Pages: 1832–1843

I. INTRODUCTION

Passive acoustic experiments have become an important tool in surveying remote areas of the sea that are difficult to investigate by more traditional techniques. Acoustic surveys of cetacean habitat are a powerful means of identifying the species present (Clark *et al.*, 1996; Clark and Charif, 1998; Stafford *et al.*, 1999; Watkins *et al.*, 2000), locating and tracking individuals (Clark *et al.*, 1996; Clark and Fristrup, 1997; McDonald *et al.*, 2001), identifying sounds associated with different regions (Stafford *et al.*, 1999; 2001), and determining patterns of seasonal distribution and relative abundance (Thompson *et al.*, 1992; Clark *et al.*, 1996; Moore *et al.*, 1998, Stafford *et al.*, 1999, 2001; Mellinger *et al.*, 2004). The extent to which this information can be obtained from acoustic data depends largely on study design, including locations and dates of recordings, instrument type (autonomous moored instrument, vessel-deployed hydrophones, etc.), sampling rate of recordings, and types of nonacoustic data collected concurrently.

In 1999, a consortium of U.S. investigators deployed an array of autonomous hydrophones (Fox *et al.*, 2001) to monitor seismic activity along the Mid-Atlantic Ridge south of the Azores (Smith *et al.*, 2002; Fig. 1). Although this experiment was designed to monitor low-frequency earth-

quakes, the instruments were also capable of recording the low-frequency calls of several species of balaenopterid whales (Payne and McVay, 1971; Winn and Perkins, 1976; Watkins, 1981; Edds, 1982; Clark, 1994). These hydrophones were located within potential migratory corridors for at least two species of baleen whales (Charif *et al.*, 2001), in an area far offshore that is not often covered by marine mammal surveys (Mellinger and Barlow, 2003, p. 23). The aim of the acoustic analyses described here was to document seasonal occurrence in the central North Atlantic of several cetacean species' vocalizations. This information will complement existing North Atlantic acoustic data on balaenopterids (Clark, 1995; Clark and Charif, 1998; Charif and Clark, 2000; Mellinger *et al.*, 2000; Charif *et al.*, 2001; Mellinger and Clark, 2003) and augment visual survey and historical whaling data on the seasonal movements and distributions of whales in the North Atlantic.

II. BACKGROUND: TYPES OF SOUNDS

The autonomous hydrophones used in this study were deployed for an experiment designed to monitor seismic activity along the Mid-Atlantic Ridge, and were configured to record sound frequencies only between 1 and 50 Hz. This includes the frequency range of the most common sounds of

blue and fin whales, as well as a portion of the frequency range of minke and humpback whale vocalizations. Sounds associated with Bryde's whales in the Atlantic are documented only from the Caribbean Sea and are known to vary geographically (Oleson *et al.*, 2003), so it was unclear what types of vocalizations might be present in the recordings. In addition, it was uncertain how to distinguish Bryde's whale sounds from other ocean sounds in the frequency band available. For these reasons, Bryde's whale sounds were excluded from the analysis. Sounds of sperm whales were above the frequency range of the instruments, and sounds of sei whales are poorly known, so these species were likewise excluded. In addition to natural sounds, manmade noise such as ship and seismic profiling sounds could be recorded in this frequency band. Because of increased interest in such manmade sounds (NRC, 2000, 2003), the distinctive signals of seismic airguns were analyzed.

The 20-Hz pulses of fin whales in the Atlantic and Pacific Oceans have been described in detail elsewhere (Thompson *et al.*, 1979; Watkins, 1981; Watkins *et al.*, 1987; Edds, 1988; Thompson *et al.*, 1992; Clark *et al.*, 2002). Typically the pulses are tones sweeping from 25–44 Hz down to 16–20 Hz over 0.5–1 s that occur with regular interpulse spacing (Watkins, 1981; Thompson *et al.*, 1992). Series of pulses occur in long, patterned, song-like sequences that change with geographic location and possibly with time (Cummings *et al.*, 1986; Watkins *et al.*, 1987; Thompson *et al.*, 1992; Clark *et al.*, 2002).

North Atlantic blue whale vocalizations were first described by Edds (1982) from the Gulf of St. Lawrence. Typically these are long, patterned sequences of sounds in the 15–20-Hz frequency band. Three types of sounds were described by Mellinger and Clark (2003). The first consists of a two-part, A–B phrase, with part A an 8-s tone, followed 0–5 s later by part B, an 11-s frequency-modulated downsweep. Usually these sounds appeared as A–B pairs, but sometimes sequences containing only part A, and occasionally only part B, were recorded. The second type of sound attributed to blue whales was a very short (2–5 s), quiet, 9-Hz tone, while the third was an arch-like sound that started at about 55 Hz, swept up to 70 Hz, then descended to 35 Hz. By far the most common call type identified by Mellinger and Clark (2003) was the A–B pair.

Series of low-frequency pulsed sounds, and sequences of these sounds (pulse trains), have been reported from minke whales (Winn and Perkins, 1976; Swift *et al.*, 1996). These pulsed sounds and pulse trains have been recorded in and near the Caribbean (Winn and Perkins, 1976; Mellinger *et al.*, 2000), the western North Atlantic (Clark, 1994), and in the St. Lawrence Estuary (Edds-Walton, 2000). Pulse trains have typically been characterized as decelerating series of pulses, although pulse rates in observations from other data sources vary, speed up, slow down, or remain constant (DKM, personal observation, 1999). The frequency range reported by Winn and Perkins (1976) was from below 100 Hz up to at least 800 Hz, although these data were filtered with a high-pass cutoff frequency of 100 Hz so the true lower-frequency component was not identified.

Song is the best known and most complex of the sounds

made by humpback whales. It consists of a series of variable sounds that occur in repetitive patterns known as units, phrases, and themes (Payne and McVay, 1971). Humpback song changes throughout the winter–spring display season, yet all whales in a population seem to make these changes at approximately the same time and sing very similar songs (Payne and Payne, 1985; Guinee *et al.*, 1983). Song characteristics have been used to identify population differences (Payne and Guinee, 1983; Winn *et al.*, 1981; Helweg *et al.*, 1990, 1998). The true function of song is unknown, but it is currently thought to be a type of male display, as all identified singers to date have been male (Tyack, 1981; Clapham and Mead, 1999). Humpback whales sing primarily on the wintering grounds (Payne and McVay, 1971; Tyack, 1981), but occasionally song or parts of song are recorded on the feeding grounds and along the whales' migratory route (Clapham and Mattila, 1990; Mattila *et al.*, 1987; McSweeney *et al.*, 1989; Norris *et al.*, 1999). Songs typically range in frequency from less than 20 Hz to over 4 kHz (Thompson and Richardson, 1995) and may be composed of a series of grunts, squeaks, moans, or other sounds. Less frequently recorded are the 50- to 10-kHz sounds made within social groups on the wintering grounds (cf. Tyack, 1983; Silber, 1986; Tyack and Whitehead, 1983) and the sounds associated with feeding (Thompson *et al.*, 1986; Cerchio and Dahlheim, 2001).

Sounds associated with seismic exploration, particularly sounds from airgun arrays, have garnered increasing interest recently as there are concerns regarding the potential impact of airgun noise on marine mammals (NRC, 2003). The loud impulses produced by airguns are created as air, pressurized within cylinders, is released suddenly into the water (Parkes and Hatton, 1986; Dragoset, 2000). The expansion of this air mass and the following contraction and re-expansion create loud explosive sounds of very short duration and broad frequency which are used to probe rock layers beneath the seafloor. The sound-pressure source level (SPSL) of a single airgun ranges from 216–232 dB *re*: 1 μ Pa at 1 m, while arrays of up to 70 airguns can produce SPSLs of up to 259 dB *re*: 1 μ Pa at 1 m (Richardson *et al.*, 1995). Typically the sounds associated with both commercial and research airguns occur repetitively every 10–20 s over a time span of days to weeks, with occasional interruptions for such actions as turning the ship that tows the airgun array.

III. METHODS

In February 1999, six autonomous hydrophones were moored along the Mid-Atlantic Ridge between 15°–35°N and 33°–50°W (Fig. 1). Hydrophones are referred to by geographic location as NW, NE, CW, CE, SW, SE (Table 1). These hydrophones monitored sound continuously, using a low-pass filter cutoff centered at 50 Hz to reduce signal aliasing, and recorded the filtered signals to disk at a sampling rate of 110 Hz. Each mooring package consisted of an anchor, an acoustic release, an autonomous hydrophone logging system, and flotation. The logging system was composed of an International Transducer Corporation 1032 hydrophone, a preamplifier and filter designed to prewhiten ocean ambient noise spectra from 1–50 Hz, a digital re-

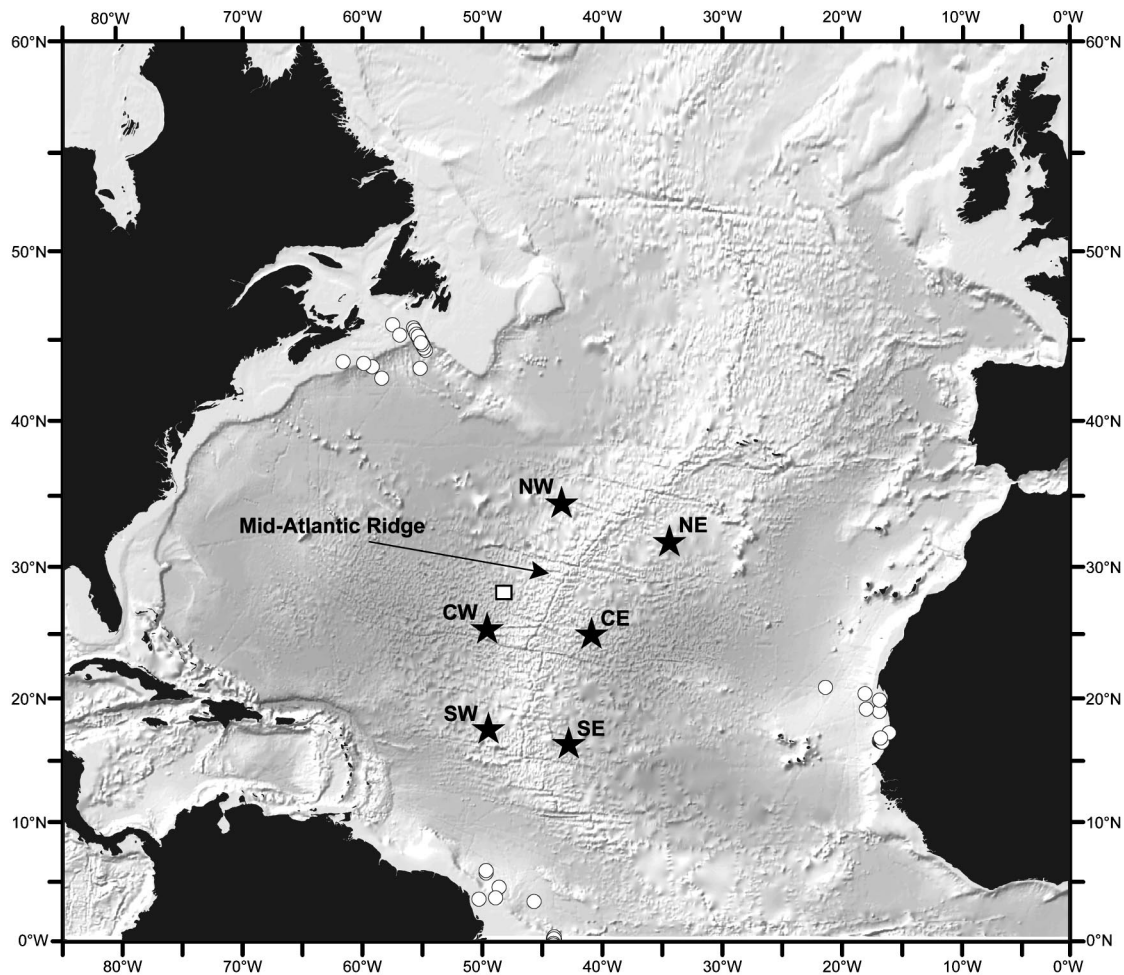


FIG. 1. Locations of six autonomous hydrophones (filled stars) moored along the Mid-Atlantic Ridge, and approximate locations (circles) of seismic airgun activity located via the array. The square represents the location of research airgun activity during the summer of 1999.

cord, and a pressure-resistant titanium case (Fox *et al.* 2001). The instruments were moored above the seafloor such that the hydrophones were suspended near the deep sound-channel axis at depths of about 800 m (Table I). The hydrophone spacing, approximately 700–800 km, was such that vocalizations from an individual whale would rarely be recorded on more than one hydrophone simultaneously, and locating vocalizing animals was not attempted. Each instrument was designed to record for just over 12 months. The

TABLE I. Approximate locations, bottom depth, and mooring depth of the six autonomous hydrophones moored near the Mid-Atlantic Ridge. Instrument depth is the number of meters from the surface and varies with year due to differences in mooring line length.

Hydrophone	Approximate mooring location	Approximate bottom depth (m)	1999–2000 instrument depth (m)	2000–2001 instrument depth (m)
SE	16°N 43°W	4565	865	767
SW	16°N 49°W	4715	815	746
CE	26°N 40°W	5105	905	866
CW	26°N 50°W	5182	982	874
NE	32°N 35°W	3927	927	925
NW	35°N 43°W	4179	679	686

data were archived on each instrument's hard drive until recovery, at which time the disks were replaced and the instrument redeployed for another 12 months.

The recovered data were monitored for whale vocalizations by visual examination of spectrograms. Continuous time–frequency spectrograms (frame and FFT size 256 samples (2.29 s), overlap 50%, Hanning window, effective filter bandwidth 1.8 Hz) of the acoustic signals recorded from the six hydrophones were displayed via a program developed by National Oceanographic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA-PMEL) written in IDL® (Interactive Data Language, Research Systems, Inc., Boulder, Co). Data for each day from Feb. 1999 to Mar. 2001 were visually examined for biological sounds, seismic activity, and manmade noise. Sounds were identified as blue, fin, or minke whale vocalizations based on their similarity to published sounds, as specified above. One other sound was identified as biological in origin because it was above the frequency band of seismic sounds, which are typically less than 20 Hz; was frequency modulated; and occurred in an irregular temporal pattern. Presence or absence of all of these sound types was recorded for each hour of data examined, and the resulting data were aggregated monthly to show the percentage of hours in each

month in which each sound type was present at least once. Recognizing that call identification can be somewhat subjective, 20 percent of the data were randomly selected and call identifications were verified by a second analyst experienced in identifying whale vocalizations. Sounds of seismic airguns were identified by their broadband impulse character, their high degree of regular repetition, and their regular occurrence for hours without stopping.

Sounds with high signal-to-noise ratio and few or no interfering sounds were selected for measurement of time and frequency characteristics. The detected biological sounds occurred in series, usually with a very regular repetition interval, and were inferred to be from one whale or one group of whales. The series would sometimes be interrupted by silent intervals that have been associated with surfacing to breathe (Cummings and Thompson, 1971; Watkins *et al.*, 1987). Occasionally two or more overlapping series would be observed, but sounds from the two series could normally be distinguished by differences in loudness, in which case only the louder series would be measured. Sound measurements were made in a *session*, an uninterrupted period of time that included part or all of one series. The sound characteristics measured included duration, initial and final frequencies, and frequency range. When appropriate, *intercall interval* (the time from the end of one call to the beginning of the following), *intergroup interval* (time between groups of pulses), and *long interval* (time between call series substantially longer than the usual intercall or intergroup interval) were measured. Statistics are reported as mean and standard deviation. Measured values were then compared to published values of species known to occur in the North Atlantic.

Due to their extremely high source levels, sounds from airgun sources were regularly recorded on three or more hydrophones, and often all six hydrophones, simultaneously. Such multiple arrivals allowed the use of arrival time delays between instruments to estimate the location of the airgun source. A modified least-squares method and software developed by NOAA-PMEL for earthquake localization (Fox *et al.*, 2001) were used to estimate the locations of seismic survey vessels.

IV. RESULTS

From Feb. 1999 to Mar. 2001, over 17 000 h of data were examined for signals of interest. Analysis identified over 6000 earthquakes (Smith *et al.*, 2002), ship noise, seismic vessel survey (airgun) sounds, sounds of fin, blue, and minke whales, and sounds that were biological in origin but could not be definitively ascribed to a particular baleen whale. The most common biological sound recorded was a series of short, downswept pulses in the 15–30-Hz range that were identifiable as fin whale calls (Fig. 2). Calls with a high signal-to-noise ratio were measured from approximately 1 h of data from each of three hydrophones (NW, NE, and CW). On average, calls lasted 0.9 ± 0.1 s (N whales=3, N calls=467). The intercall interval between the “classic” calls (Clark *et al.* 2002) averaged 17.5 ± 0.4 s (N whales=3, N calls=380). However, a longer interval (38.1 ± 1.9 s, N whales=3, N calls=80) that sometimes included a pulse of

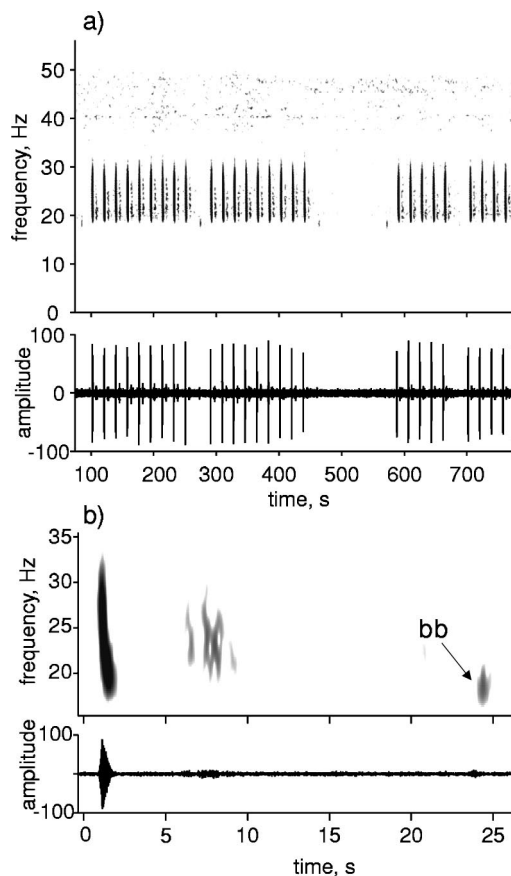


FIG. 2. (a) Spectrogram and time series of a series of fin whale calls recorded on the CW hydrophone, 15 January 2000 [spectrogram parameters: frame and FFT length 4.7 s (512 samples), overlap 0.75, Hamming window, for a filter bandwidth of 0.9 Hz]. (b) Detail of fin whale classic pulse and backbeat (bb; arrow) [spectrogram parameters: frame length 0.6 s (64 samples), FFT length 512 samples, overlap 0.9375, Hamming window, for a filter bandwidth of 7 Hz].

the type Clark *et al.* (2002) refer to as a “backbeat” was also observed. As this backbeat was not always visible, most likely due to the lower amplitude of this type of call, we did not make detailed measurements of the time between backbeat and classic pulses. The longer intervals between pulse series, referred to as “rests” by Watkins *et al.* (1987), averaged 135.3 ± 21.9 s (N whales=3, N calls=9).

Fin whale calls were detected seasonally on all six hydrophones [Fig. 3(a)]. The majority of pulses was observed on the northern hydrophones from October to April, with peak detections in the winter months. In some months these calls were detected in over 85% of the hours examined. The same seasonal pattern was seen on the central hydrophones, although the proportion of hours with calls was much lower at these latitudes. At the southern hydrophones, relatively few hours with fin whale calls were observed. In the 2 years of the study, the seasonal occurrence of fin whale sounds was similar with the exception of the NE hydrophone, where fin whale calls occurred more often and later into the year in 2000–2001 than in 1999–2000.

The North Atlantic blue whale A–B phrase was the second most common whale sound recorded by this array [Fig. 4(a)]. These sounds occur in long, patterned series, interrupted by gaps that may represent breathing intervals (Cum-

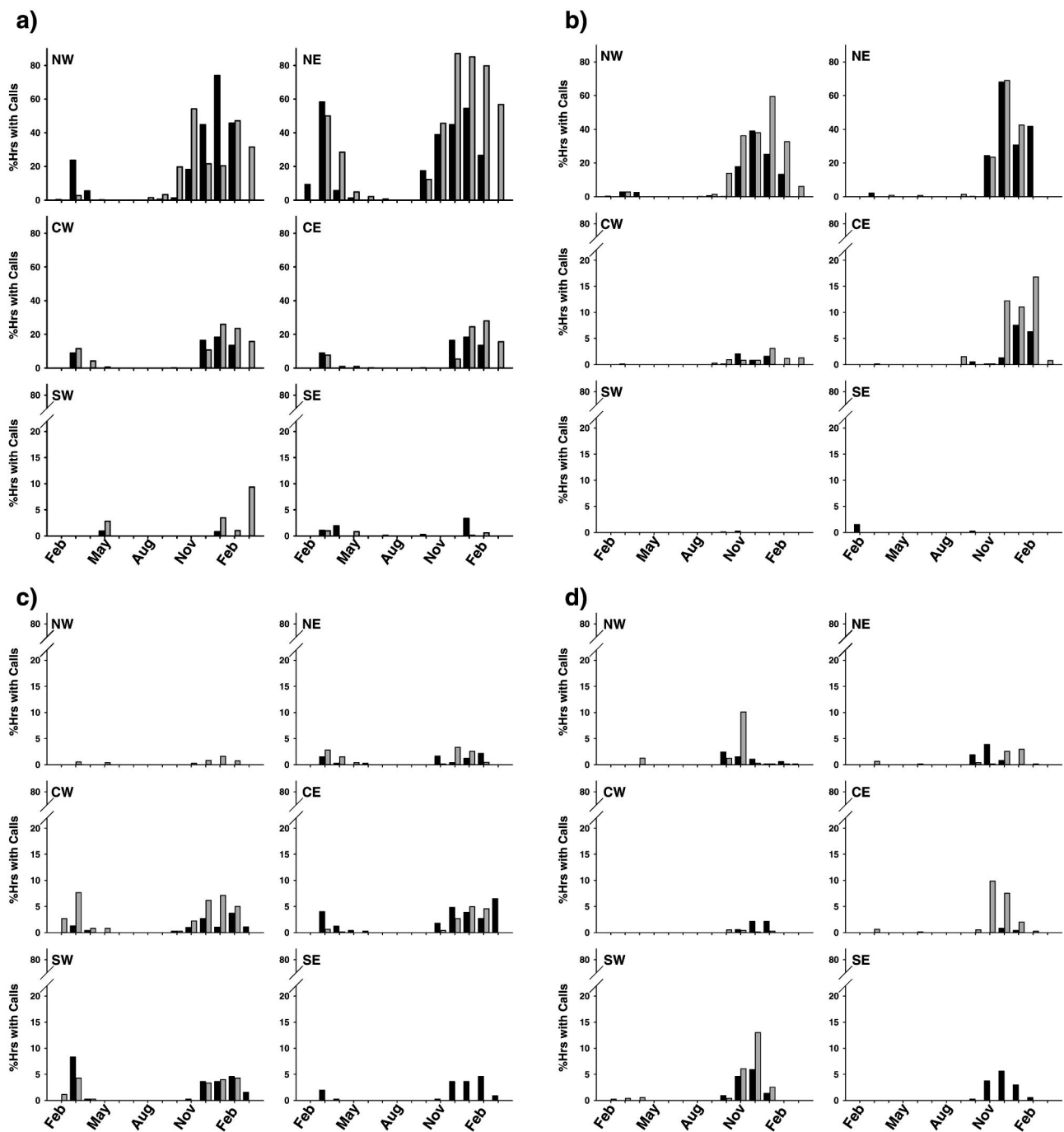


FIG. 3. Histograms of seasonal patterns of calls detected by the six autonomous hydrophones. Dark bars are data from Feb. 1999–Feb. 2000; light bars from Feb. 2000–Mar. 2001. Bars represent proportion of hours per month in which calls were detected. Seasonal patterns of sounds from (a) fin whales; (b) blue whales; (c) minke whales; (d) downswept vocalizations from unidentified baleen whales.

mings and Thompson, 1971). Here, we use the terminology of Mellinger and Clark (2003) to describe these sounds. Time–frequency characteristics were measured for a total of 794 blue whale phrases from ten different sessions when blue whale sounds were present, representing ten time periods and three locations in the North Atlantic. Of these phrases, 556 were A-only phrases and 227 were A–B phrases; 11 A–B phrase sequences also included arch sounds. In A-only phrases, part A swept from 18.4 ± 0.2 Hz to 17.6 ± 0.4 Hz and lasted 11.8 ± 1.1 s ($N=10$). The time between consecutive A-only phrases was 60.0 ± 3.8 s ($N=8$). In A–B phrases, part A lasted an average of 11.1 ± 1.6

s ($N=8$), and part B swept from 18.3 ± 0.2 Hz to 16.0 ± 0.4 Hz over 9.0 ± 0.9 s ($N=8$). Time between the two phrase parts was 4.8 ± 0.8 s ($N=8$). The ratio of the numbers of parts A and B within a series varied from 1 to 155 over the time periods during which calls were measured ($\bar{x} = 26.3 \pm 52$, $N=8$). The number of phrases in each sequence was also quite variable, ranging from 2 to 11 ($\bar{x} = 6.5 \pm 2.6$, $N=10$). Arch sounds were noted in only one time period, and because the upper-frequency limit of the recordings was 50 Hz, only the lower-frequency portions of these sounds were recorded [Fig. 4(b)] Eleven arch sounds were measured.

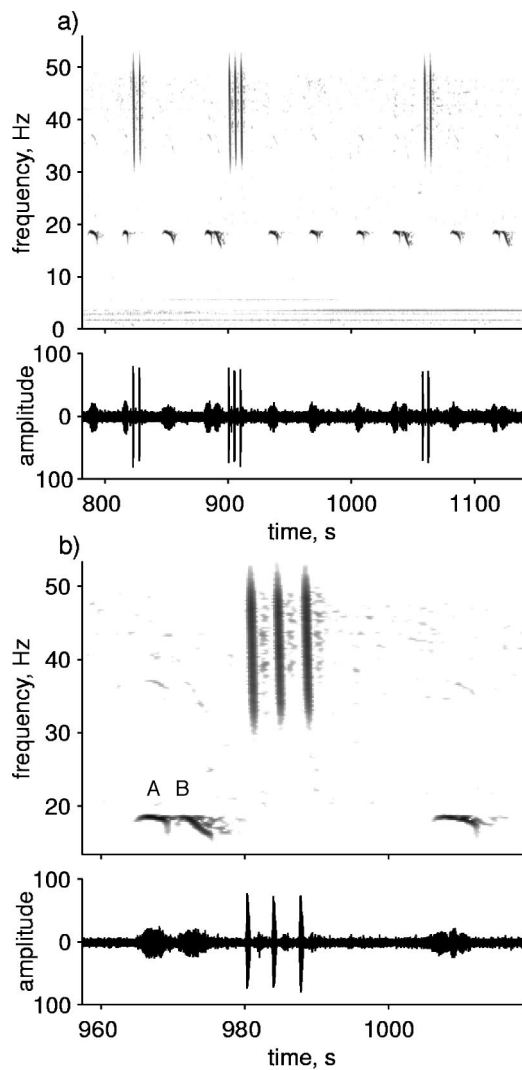


FIG. 4. (a) Spectrogram and time series of a series of blue whale AB calls and arch sounds recorded on the NE hydrophone, 15 November 1999 [spectrogram parameters same as in Fig. 2(a)]. (b) Detail of blue whale call [spectrogram parameters same as in Fig. 2(a) except overlap is 0.875].

These occurred in groups of 2–3 during only two of the 20 sequences measured for this time period. Arch sounds swept from the top of our recording frequency range (ca. 50 Hz) down to 32.0 ± 1.0 Hz. On average, these sounds lasted 2.5 ± 0.4 s ($N=11$).

Atlantic blue whale calls were detected primarily on the northern hydrophones during the winter months [Fig. 3(b)]. Trends were similar between the 2 years. Call occurrence peaked in December and January on both the NW and NE hydrophones. As with the fin whale data, the seasonal pattern was similar on the CE and CW hydrophones but at greatly reduced rates. Call occurrence on the southern hydrophones was quite low in both years.

Series of pulsive calls (Fig. 5) were detected in both years [Fig. 3(c)] in the hydrophone recordings. These appeared to be the lower-frequency part of pulse trains that have been recorded from minke whales (Winn and Perkins, 1976; Swift *et al.*, 1996), having the same approximate pulse repetition rate and pulse train length (Mellinger *et al.*, 2000). Measurements of frequency and interpulse interval were

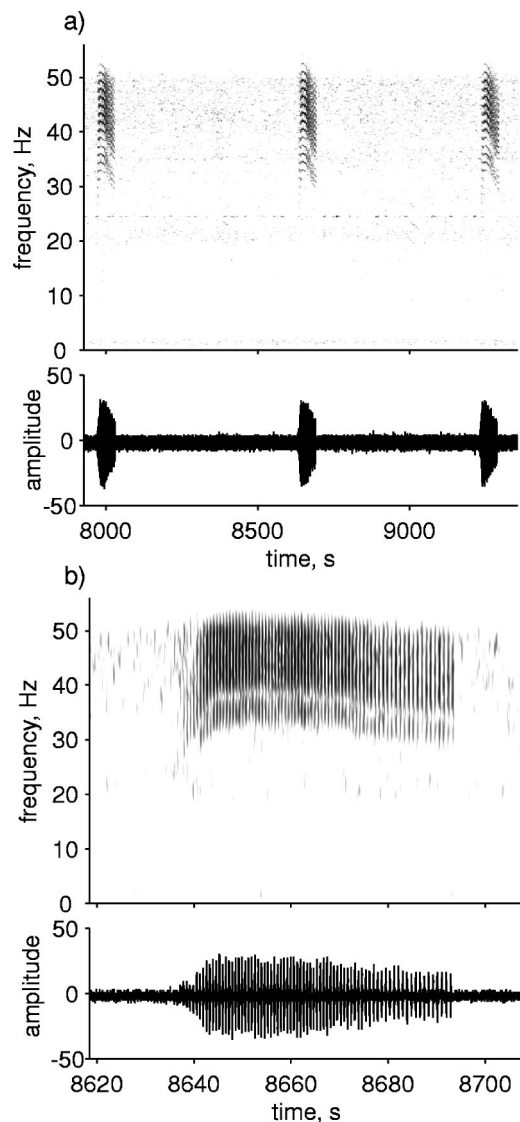


FIG. 5. Spectrograms and time series minke whale calls recorded on the SE hydrophone, 27 January 2000. (a) Series of minke whale calls. Because of the cutoff frequency of our hydrophones (50 Hz), these are considered partial calls, but are still similar enough to minke whale calls recorded elsewhere to be identifiable [spectrogram parameters: frame length 9.3 s (1024 samples), FFT length 2048 samples, overlap 0.5, Hamming window, for a filter bandwidth of 0.4 Hz]. (b) Detail of minke whale call. Note the decelerating pulse rate, a feature of nearly all of the calls examined [spectrogram parameters same as Fig. 2(b) except overlap is 0.75].

made at the beginning, middle, and end of each pulse train because pulse rate and frequency band varied within the train. On average, the interpulse interval calculated from individual session averages ($N=26$) was 0.7 ± 0.1 s at the beginning of a pulse train, 0.7 ± 0.1 s at the middle of a pulse train, and 0.9 ± 0.04 s at the end. The ending interpulse interval was significantly longer (*t*-test, $p < 0.05$), indicating that these pulse trains slowed down toward the end. The pulse trains, averaged over the sequences measured ($N=24$), contained 68 ± 6 pulses and lasted 48.0 ± 4.8 s, and successive trains occurred at intervals of 528 ± 94 s ($N=25$). The mean lower frequency was 30.6 ± 4.4 Hz ($N=24$), with a minimum frequency over all measured pulse trains of 21.0 Hz.

Pulse trains occurred most often during the months of December through March [Fig. 3(c)] and were most common

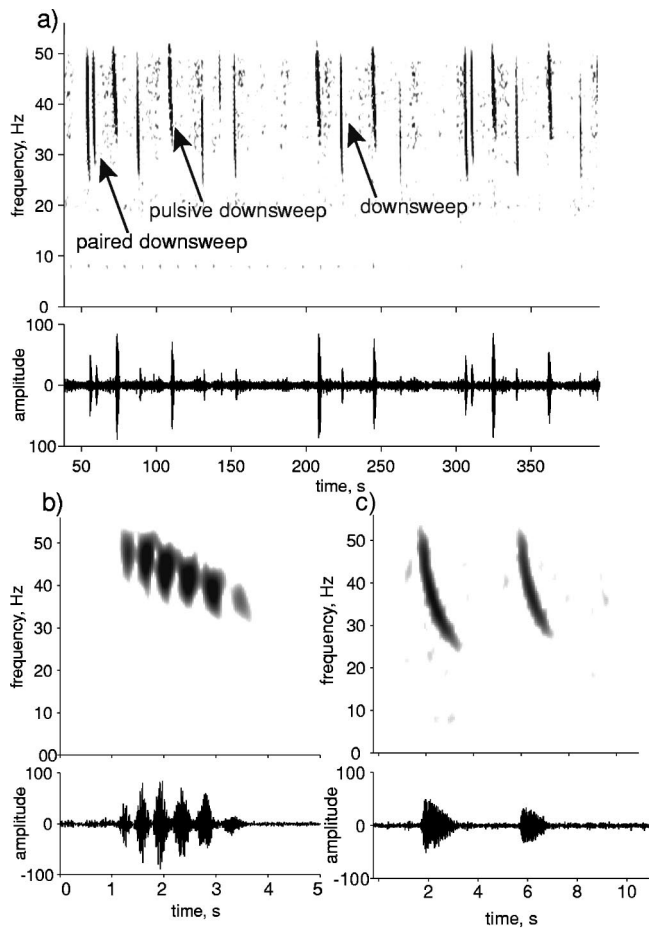


FIG. 6. (a) Spectrogram and time series of calls that are likely from a baleen whale recorded on the CW hydrophone, 26 November 1999 [spectrogram parameters: frame and FFT length 2.3 s (256 samples), overlap 0.5, Hamming window, for a filter bandwidth of 1.7 Hz]. This call typically consists of 1 or 2 downsweeps followed by a pulsed downsweep. (b) Detail of pulsed downsweep [spectrogram parameters: frame length 0.3 s (32 samples), FFT length 512 samples, overlap 0.875, Hamming window, for a filter bandwidth of 14 Hz]. (c) Detail of downsweep [spectrogram parameters: frame length 0.6 s (64 samples), FFT length 256 samples, overlap 0.875, Hamming window, for a filter bandwidth of 7 Hz].

on the central and southern hydrophones. This same seasonal pattern was seen on the NE hydrophone but at much lower rates of occurrence. Almost no pulse trains were detected on the NW hydrophone.

Less frequently, sounds were observed that swept from the maximum frequency of the autonomous hydrophone instrument, 50 Hz, down to approximately 30 Hz (Fig. 6). These sounds, here called *downsweep vocalizations*, sometimes occurred in pairs, and due to their general similarity to known baleen whale sounds, it is likely that these are baleen whale vocalizations. cursory examination of the data revealed that there were typically two types of downsweep vocalizations: a simple, 3.0 ± 0.1 -s downsweep from about 49.7 ± 0.9 Hz down to 29.0 ± 0.5 Hz ($N=6$), and a second, slightly longer (4.11 ± 0.1 s) sound more pulsed in nature. This second sound was recorded less often than the simple downsweep, was less likely to occur in pairs, and typically swept from about 50.2 ± 0.2 Hz down to 34.4 ± 0.4 Hz ($N=5$). There was no obvious pattern to the order of simple downsweeps and pulsed downsweeps. Simple downsweeps

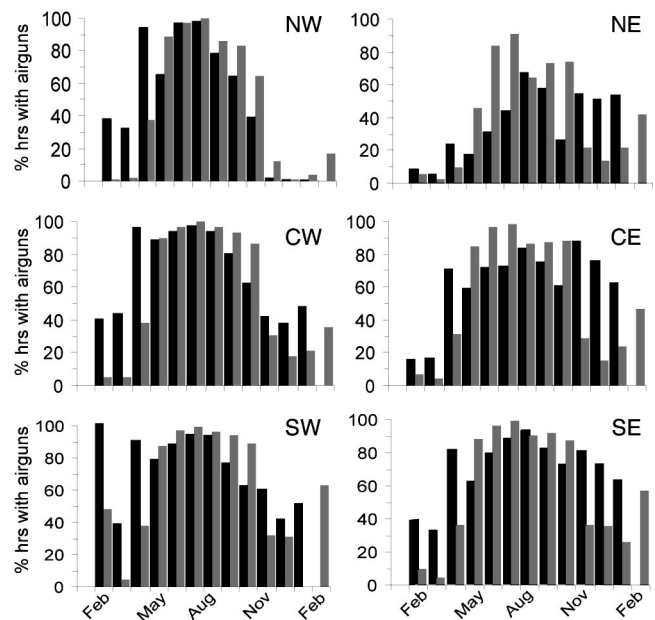


FIG. 7. Seasonal patterns of airgun pulses detected by the six autonomous hydrophones. Dark bars are data from Feb. 1999–Feb. 2000; light bars from Feb. 2000–Mar. 2001. Bars represent proportion of hours per month in which calls were detected.

often occurred in series that did not include pulsed downsweeps. The exact nature of these sounds was difficult to determine, as it appeared there was additional content above the cutoff frequency of the recording system's filter. Both types of downsweeps were recorded primarily in winter and resemble a variety of sounds, including those recorded in the presence of blue whales in the St. Lawrence Estuary (C. Berchok, personal communication 2003), sounds described from the Norwegian Sea that are likely from fin whales (C. Clark, personal communication 2003), and the lower frequencies of some parts of humpback whale songs. In addition, these two sounds were often made in sequences exceeding 15 min that included no time gaps. If these were parts of a humpback whale song, the animal was apparently singing the same phrase or theme repeatedly. These sounds were recorded the least often of all those discussed in this manuscript, and were recorded most often on the central hydrophones in the late fall and winter months [Fig. 3(d)].

Sounds associated with seismic airguns were recorded routinely on all hydrophones, and trends were similar in the two years (Fig. 7). Typically airguns were heard every 10–20 s (Fig. 8). Although airgun sounds tended to dominate recordings during the summer months, loud whale vocalizations could still be detected during intense airgun activity (Fig. 8). Occasionally the array recorded airguns from more than one location, masking cetacean sounds and on four occasions making the spectrogram data impossible to use. The high received level of these impulses on multiple hydrophones made it possible to estimate the locations of the ships conducting the airgun surveys. During the summer months, airguns operated off Nova Scotia, Canada, probably in support of exploration in the Sable Island region (Fig. 1). From spring through fall seismic vessels, presumably commercial, were located working off the coast of western Africa and

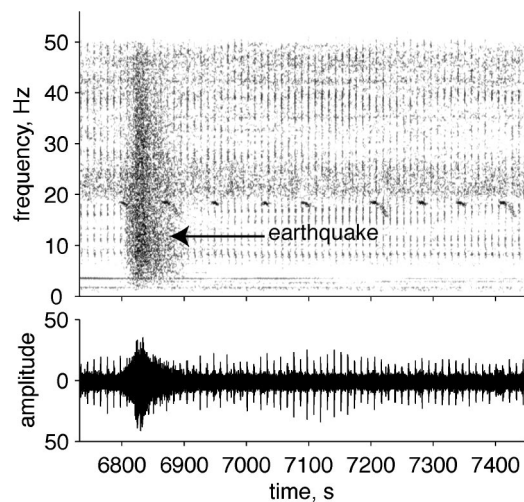


FIG. 8. (a) Spectrogram and time series of a series of airgun pulses, an earthquake (arrow), and a series of blue whale A–B calls recorded on the NE hydrophone, 11 February 2000 [spectrogram parameters same as in Fig. 2(a)].

northeast of Brazil. Seismic vessels operating in other areas of active exploration, such as the North Sea and the Gulf of Mexico, were not observed by this array due to bathymetric blockage.

V. DISCUSSION

Vocalizations of at least three, and possibly four, species of baleen whales were recorded on this array, despite its remote, offshore location. For all species and all hydrophones, most vocalizations were recorded in the late fall, winter, and early spring. This distinct seasonal pattern in detections may be due to changes in the vocal activity or migratory behavior of these whales. The wintertime peak in vocalizations apparent in our data coincides with what is thought to be the breeding season, and what is known to be the calving season, for baleen whales (Gaskin, 1982; Stewart and Leatherwood, 1985). It is male humpback whales that sing complex songs (Tyack, 1981; Darling and Bérubé, 2001), and there is limited evidence that it is male blue whales (McDonald *et al.*, 2001) and fin whales (Croll *et al.*, 2002) that produce loud, repetitive series of vocalizations. These long, repeating series of sounds made by male baleen whales during the winter months may be an advertisement signal (Tyack, 1981; Watkins *et al.*, 1987), similar to that produced by males of many terrestrial species during the breeding season (cf. Clutton-Brock and Albon, 1979; Searcy and Yasukawa, 1996; Gerhardt and Huber, 2002). Vocal advertisement could potentially occur year-round, as baleen whales are known to produce sounds in all months of the year (Clark and Gagnon, 2002), but probably peaks during the wintertime breeding season. Thus, increased vocal activity during the breeding season may be one explanation for the seasonal pattern of detections in these data.

In addition to this potential seasonal change in vocal behavior, the high numbers of detections during the winter months may also be due to an increase in the number of vocalizing individuals in the areas monitored by our hydrophones. Most baleen whales are distributed in productive,

high-latitude regions during the summer, and migrate to less-productive, lower-latitude areas, sometimes far offshore, for calving and breeding in the winter months (Gaskin, 1982). Our array is in an area that could be a migratory destination or route for baleen whales. In other areas of the North Atlantic, the number of vocalizations detected has been strongly correlated ($r > 0.85$) with the estimated number of individuals heard (Clark and Charif, 1998), and it therefore seems likely that the higher numbers of detections here are indicative of more vocalizing whales in the region. Because blue and fin whales vocalize in all months of the year (Clark and Charif, 1998; Charif and Clark, 2000; Stafford *et al.*, 2001; Clark and Gagnon, 2002) and very few of these vocalizations are detected on this mid-Atlantic array during the summer months, the number of vocalizing animals in the vicinity of this array during the summer months must be small. Airgun activity also peaks during the summer, but it is unlikely airguns are completely obscuring whale sounds, as calls are detected during some months of frequent airgun occurrence in the fall, and the repetition rate of airguns is such that most whale sounds can be detected between pulses (Fig. 8) (cf. Clark and Charif, 1998). Thus, the seasonal signal in our data may be due to changes in both the vocal activity and the distribution of the whales. These explanations are not mutually exclusive, nor does the explanation for one species necessarily apply to other species. These hypotheses cannot be tested with the data presented here but suggest directions for future research.

A. Fin and blue whales

The most common vocalizations recorded on our array were sounds from fin and blue whales. Fin whale detections far outnumbered those from blue whales in this study, despite the fact that we could probably detect the loud, very-low-frequency blue whale calls (SL=188 dB *re*: 1 μ Pa at 1 m; Cummings and Thompson, 1971) at greater distances from our array than the somewhat quieter, higher-frequency fin whale sounds (SL=183 dB *re*: 1 μ Pa at 1 m; Cummings and Thompson, 1994). The fin whale was also the species heard most often on other North Atlantic arrays (Clark, 1995; Clark and Charif, 1998). This is likely a reflection of the relative number of animals; the fin whale population estimate for the North Atlantic is approximately 50 000 animals, while that of the blue whale is 1000–2000 animals (Sigurjonsson, 1995).

Both fin and blue whale sounds were recorded primarily on the two northern hydrophones (~ 32 – 35 $^{\circ}$ N), less on the central hydrophones (~ 26 $^{\circ}$ N), and least on the southern hydrophones (~ 17 $^{\circ}$ N). This pattern agrees with what we know of their distribution from whaling, visual survey, and other acoustic survey data. Very little is known of fin and blue whale migratory movements, and it is currently unclear where calving, mating, and wintering occur (Jonsgard, 1966; Waring *et al.*, 2002). For both species, the summer feeding range is limited to the north by the ice edge, and may extend as far south as the British Isles in the eastern Atlantic and the Carolinas in the western Atlantic (Jonsgard, 1966; Rorvik and Jonsgard, 1981). In winter, this distribution likely shifts further south and offshore (Kellogg, 1929; Rorvik and Jonsgard, 1981; Sigurjonsson, 1995). Sighting and stranding data

from fall and winter months record these species as far south as the Gulf of Mexico, the Mediterranean Sea, and the coast of northwest Africa ($\sim 21^\circ\text{N}$) (Kiripichnikov, 1950; Jonsgård, 1966; Sergeant, 1977; Rorvik and Jonsgård, 1981; Sigurjonsson, 1995). Given that our hydrophone array is far offshore and south of estimated fin and blue whale habitat, it is not surprising that the majority of detections was on the northernmost hydrophones. The near absence of these sounds on the southernmost hydrophones may show that blue and fin whales do not vocalize at this latitude or that they do not occur this far south.

B. Minke whales

Although the sampling rate of our hydrophones prevented us from detecting the full 25–800-Hz bandwidth of minke whale pulse trains (Winn and Perkins, 1976; Mellinger *et al.*, 2000), we did record at least some of the lower-frequency parts of these sounds. Current population estimates, based on data from visual surveys and whaling records, suggest that there are over 100 000 minke whales in the North Atlantic (Sigurjonsson, 1995). Despite their abundant numbers, minke whale sounds were recorded relatively rarely by our array; these sounds were typically detected in less than 10% of the hours sampled. Minke whale sounds are of lower amplitude (~ 165 dB *re*: $1 \mu\text{Pa}$ at 1 m; Schevill and Watkins, 1972) than blue and fin whale vocalizations and therefore may be detected by our hydrophones only when whales are in close proximity to the array.

Unlike the fin and blue whale sounds, most of our minke detections were on the central and to a lesser extent the southern hydrophones. Few detections were made on the northern hydrophones, and the majority of these was on the NE hydrophone. Minke whale distribution is generally limited to the north by ice, and to the south distribution extends to the tropics, including Bermuda, Puerto Rico, the West Indies (Winn and Perkins, 1976; Mitchell, 1991; Mellinger *et al.*, 2000) and possibly to more offshore, deep-ocean waters in winter (Horwood, 1990; Mitchell, 1991). Very little is known of the distribution of minke whales in the southeastern North Atlantic. There are a few scattered sightings of minke whales at $20^\circ\text{N } 20^\circ\text{W}$ and at $11^\circ\text{N } 22^\circ\text{W}$ (Folkow and Blix, 1991) and in the Azores during May and June, and to a lesser extent July and August (Bento, 2002). It is unclear why we did not record more minke whale vocalizations on the northern hydrophones ($\sim 31^\circ\text{N}$) given this species's distribution; perhaps vocalizing minke whales do not move within range of our array very often at this latitude, or perhaps they are not vocalizing while at this latitude. Many minke pulse trains may also have been missed because they were above the 50-Hz upper frequency limit of the filtering/recording system. More data will be needed to explain the paucity of recordings on these northern hydrophones.

As with the fin and blue whale data, there was a marked seasonal pattern in detections of minke whale vocalizations. Pulse trains were detected from November to April, peaking in December–February; very few sounds from minke whales were recorded during the summer months. This pattern agrees with findings of other acoustic studies in the North Atlantic. In the West Indies and Bermuda, sounds attributed

to minke whales were recorded from October to April (Gagnon and Clark, 1993; Clark, 1994; Nishimura and Conlon, 1994; Clark, 1996) and in the eastern North Atlantic ($28^\circ\text{N } 20^\circ\text{W}$) in December (Folkow and Blix, 1991). Northeast of our array, minke whale sounds were detected from September to November in SOSUS data (Clark *et al.*, 2003). If minke whales breed in open ocean areas (Sigurjonsson, 1995), they could be moving into range of our array, and increasing their vocal activity during the winter months.

C. Downsweep vocalizations

In our data, detections of the simple and pulsive downsweep vocalizations that are potentially baleen whale sounds were quite limited. Most detections were during the winter months, but a few detections were as late as April. These sounds could be from humpback whales; we would expect to record humpback song or song fragments on our hydrophones during the winter, as this array is positioned within the migratory route of, and adjacent to, humpback wintering grounds (Charif *et al.*, 2001; Clapham and Mead, 1999; Stevick *et al.*, 1998; Palsboll *et al.*, 1997). Most sounds produced by singing humpbacks are above the 50-Hz cutoff frequency for our instruments, so identifying these sounds definitively as humpback whale vocalizations is difficult. Clark and Charif (1998) point out that humpback whale sounds are of lower intensity than other baleen whale sounds, and so detection range will be limited. These sounds could also be from blue or fin whales, as they are similar to sounds tentatively attributed these species (respectively, C. Berchok and C. Clark, personal communication 2003). In the future we plan to increase the sampling rate of the hydrophones to help determine the true nature of these sounds.

D. Airguns

Since this hydrophone array was deployed, the periodic impulses produced by seismic exploration vessels operating around the Atlantic basin were the dominant signal detected. Concern over the potential effects of anthropogenic noise on marine life has been such that the National Research Council of the (U.S.) National Academy of Science has commissioned three studies on this topic to date (NRC 1994, 2000, 2003). Although seismic airgun arrays are designed to direct the majority of emitted energy downward through the seafloor, their sound emission horizontally is also significant (NRC, 2003). Airgun survey vessels were often located 3000 km or more from our array (Fig. 1), yet airgun pulses were still clearly recorded on each hydrophone. The broadband frequency range and repeated firing of these guns make them a major contributor to the low-frequency sound field in the North Atlantic.

Airgun activity in shallow water has been shown to significantly damage the ears of fish (McCauley *et al.*, 2000) and has been implicated in the stranding of beaked whales (Malakoff 2002; NRC 2003). Its effect on the baleen whales studied here is unknown; possible effects include masking of conspecific sounds, increased stress levels, changing vocalizations, and ear damage (Richardson *et al.*, 1995). Most of

the seismic vessels we located were operating in marine mammal habitat, including that of the critically endangered northern right whale.

Airgun pulses were recorded year-round but were most common from late spring through fall. This pattern is the opposite of the peak occurrences for all baleen whale calls. It is possible that the seasonal patterns seen in baleen whale calls are due to airgun interference: that is, the calls are produced in the summer months but obscured by airguns. However, because calls are detected during some months of frequent airgun occurrence in the fall, because the repetition rate of airguns is such that most whale sounds can be detected between pulses (Fig. 8), and because the data were visually inspected, we don't believe that many calls were missed due to interference (cf. Clark and Charif, 1998).

VI. CONCLUSIONS

Sounds from fin, blue, minke, and possibly another species of baleen whale were recorded on six autonomous hydrophones moored near the Mid-Atlantic Ridge. The low sampling rate of our recordings and the unknown acoustic repertoire of other species made the identity of some vocalizations uncertain. Recording data at a higher sampling rate could help determine the origin of this call type and provide data on the full frequency range of minke whale calls and the recently documented short, narrow-band sounds produced by Bryde's whales (*B. edeni*) (Oleson *et al.*, 2003). In addition, given the recent interest in the contribution of airgun noise to the marine environment and its potential adverse effects on marine mammals (cf. NRC 2000, 2003), we recommend continued monitoring of this area airgun sounds and a more formal measurement of this source of noise.

The utility of remote acoustic monitoring has been well established for determining the occurrence of calling whales in regions and during times that are not feasible for traditional visual survey methods (Clark and Charif, 1998; Stafford *et al.*, 1999, 2001; Watkins *et al.*, 2000; Mellinger *et al.*, 2003, 2004). The constraints of interpreting such acoustic data include the difficulty of associating the number of sounds recorded with the number of animals present, the detection range of the sounds, and seasonal, behavioral, and demographic variation in calling behavior data (Clark and Charif, 1998; Mellinger and Barlow, 2003). If remotely acquired acoustic data are to provide the information necessary for the management and recovery of large whales, future efforts must address these obstacles. Despite the limitations, the acoustic data from this array have given us insight into the vocal behavior and occurrence of highly mobile, migratory animals in a very remote part of the Atlantic Ocean that has traditionally been difficult to survey.

ACKNOWLEDGMENTS

Funding for the deployment, maintenance, and data analysis for the hydrophone array along the Mid-Atlantic Ridge was provided by the National Science Foundation via grants awarded to R. P. Dziak (Grants OCE-9811575, OCE-0137164, and OCE-0201692). This work was also supported by ONR Contracts N00014-00-F-0395 and N00014-03-1-

0099 awarded to D. K. Mellinger. Development of the hydrophones was provided by in-kind funding from NOAA-PMEL. We are indebted to Haru Matsumoto for design and construction of the hydrophones used in this experiment; Andy Lau for the development of the PMEL software used for analysis of the data; Matt Fowler, Joe Haxel, Sarah Follett, and Rita Bento for their help with various stages of the analysis; and Sara Heimlich and two anonymous reviewers for manuscript revisions. This is PMEL contribution #2603.

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